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Evaluation of the EPA PLUVUE Model and the ERT Visibility Model Based on the 1979 VISTTA (Visibility Impairment Due to Sulfur Transformation & Transport in the Atmosphere) Data Base

Systems Applications, Inc.
San Rafael, CA

Prepared for

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This report presents the results of the evaluation of the EPA PLUVUE model and the ERT Visibility model based on the 1979 EPA VISTTA data base which was obtained during the June-July and December 1979 field programs conducted at the Navajo Generating Station. The overall evaluations were performed for three different types of background conditions: clear sky, dark mountain and hazy sky.

Results of the evaluation of the two models indicate: (a) PLUVUE tends to overestimate plume visual effects; the average absolute relative errors in plume contrast are 69, 83, 69 and 154 percent at 405, 450, 550 and 630 nm, respectively; (b) the ERT Visibility model tends to underpredict the plume visual effects; the average absolute relative errors in plume contrast are 42, 37, 30 and 262 percent at the above wavelengths; (c) the dispersion module in each model appears to contain the primary source of uncertainty in model predictions; (d) the chemistry module in each model shows reasonable agreement between predictions and measurements of the NO_2/NO_x ratio; (e) the optics module in each model compares satisfactorily with the case studies.

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PREFACE

This report presents the results of the evaluation of the EPA PLUVUE model and the ERT Visibility Model based on the 1979 EPA VISTTA data base, which was obtained during the June-July and December, 1979, field programs conducted at the Navajo Generating Station. This study was performed under Contract 68-02-3225 with the EPA-ESRL Office of Regional Studies under the direction of Dr. William E. Wilson. This report was produced under Contract 68-02-3582 with the U.S. Environmental Protection Agency (EPA). Thanks are due to Mr. James Dicke of the EPA Office of Air Quality Planning and Standards for his continuing interest and helpful suggestions during the course of this study. Thanks are also due to Dr. L. Willard Richards of Meteorology Research, Inc., for providing useful information and comments regarding the VISTTA field measurements. Production of this report was due largely to the dedicated efforts of Sandra Golding and Carol Lawson, technical editors, as well as several members of the Publications Center.

CONTENTS

PREFACE..... iii

LIST OF TABLES..... vi

1 OVERVIEW AND SUMMARY..... 1

BACKGROUND..... 1

CONCLUSIONS..... 3

ORGANIZATION OF THE REPORT..... 4

2 OVERVIEW OF THE DATA BASE..... 5

3 PERFORMANCE MEASURES..... 10

4 OVERALL EVALUATION OF PLUVUE..... 16

5 OVERALL EVALUATION OF THE ERT VISIBILITY MODEL..... 26

APPENDIX A: EVALUATION OF THE MODULES OF PLUVUE..... 32

APPENDIX B: EVALUATION OF THE MODULES OF THE ERT VISIBILITY MODEL..... 46

APPENDIX C: SENSITIVITY/UNCERTAINTY ANALYSIS OF PLUVUE..... 55

APPENDIX D: MODIFICATIONS TO THE ERT VISIBILITY MODEL COMPUTER CODE..... 61

REFERENCES..... 64

LIST OF TABLES

1 Input Data for PLUVUE and the ERT Plume Visibility Model (1979)..... 9

2 Comparison of Measured and Predicted Plume/Sky Intensity Ratios for the Overall Evaluation of PLUVUE..... 17

3 PLUVUE Performance Analysis of 20 Case Studies under Clear-Sky Background Conditions..... 22

4 PLUVUE Performance Analysis of 2 Case Studies under Dark-Mountain Background Conditions--Normalized Residual Statistics..... 23

5 PLUVUE Visibility Model Performance Analysis of 5 Case Studies under Hazy-Sky Background Conditions--Normalized Residual Statistics..... 23

6 Comparison of Measured and Predicted Plume/Sky Intensity Ratios for the Overall Evaluation of the ERT Visibility Model..... 27

7 ERT Visibility Model Performance Analysis of 20 Case Studies under Clear-Sky Background Conditions..... 28

8 ERT Visibility Model Performance Analysis of 2 Case Studies under Dark-Mountain Background Conditions--Normalized Residual Statistics..... 29

9 ERT Visibility Model Performance Analysis of 5 Case Studies under Hazy-Sky Background Conditions--Normalized Residual Statistics..... 29

SECTION 1

OVERVIEW AND SUMMARY

BACKGROUND

To evaluate the impact of plumes from emissions sources on atmospheric visibility in class I areas, the U.S. Environmental Protection Agency (EPA) has had to develop both monitoring and modeling capabilities. Consequently, Systems Applications, Inc. developed a plume visibility model for the EPA (Latimer et al., 1978; Johnson et al., 1980) as part of its obligation to supply technical guidance to states and federal land managers who enforce the newly promulgated visibility regulations.

Because the performance of a plume visibility model must be carefully evaluated before it can be used in a predictive mode, one goal of the EPA-sponsored VISTTA (Visibility Impairment Due to Sulfur Transformation and Transport in the Atmosphere) field programs was the provision of a data base needed to evaluate visibility models. The June-July and December, 1979, EPA VISTTA field programs consisted of the recording of a set of coordinated measurements for characterizing the impact of a specific power plant--the Navajo Generating Station--located in the vicinity of mandatory class I areas. Measurements of the emission rates from the stacks and of the attendant meteorological conditions were carried out. Telephotometers were used to measure the visual effects of the plume, and plume concentration measurements were performed from an instrumented airplane. The aircraft made continuous measurements of SO_2, NO_x, and O_3 concentrations and aerosol-scattering coefficients. To the extent possible, the flight paths were aligned with the telephotometer sight paths so that concentration measurements throughout the plume were made at the plume downwind

distance corresponding to the telephotometer measurements. This report presents the evaluation of two plume visibility models--PLUVUE, and the ERT Visibility Model, version 3--based on the 1979 VISTTA data base. PLUVUE was developed by Systems Applications, Inc. for the U.S. Environmental Protection Agency. The model, which has been described by Latimer et al. (1978), and a comprehensive user's guide developed by Johnson et al. (1980) are available from the EPA. The ERT Visibility Model was developed by Environmental Research and Technology, Inc. (ERT). A technical description and user's guide are available from ERT (Environmental Research and Technology, Inc., 1980).

The overall evaluations of PLUVUE and the ERT Visibility Model were performed for three different types of background conditions:

> Clear-sky background (20 case studies using data from 13 July, 7 December, and 15 December, 1979).

> Dark-mountain background (2 case studies using data from 28 June 1979).

> Hazy-sky background (5 case studies using data from 4 December 1979).

Simulations were carried out on the basis of emission, meteorological, and background air quality data--the inputs listed in the 1979 VISTTA data base (Seigneur et al., 1981).

Evaluation of the dispersion and chemistry modules was conducted from case studies in which the aircraft had flown through the approximate plume centerline. The evaluation of the optics module was conducted for 10 cases from 7 December 1979, for which there was good alignment between the telephotometer sight path and the aircraft flight path. Thus, the aircraft measurements could be used as direct inputs to the optics modules.

CONCLUSIONS

Results of the evaluation of PLUVUE and the ERT Visibility Model indicate the following conclusions for the conditions considered:

- PLUVUE tends to overpredict the plume visual effects; the average absolute relative errors in plume contrast are 69, 83, 69, and 154 percent at 405, 450, 550, and 630 nm, respectively.

- The ERT Visibility Model tends to underpredict the plume visual effects; the average absolute relative errors in plume contrast are 42, 37, 30, and 262 percent at 405, 450, 550, and 630 nm (the wavelengths used for the telephotometer measurements), respectively.

- The dispersion modules of both PLUVUE and the ERT Visibility Model appear to contain the primary source of uncertainty in model predictions: plume dispersion is generally underestimated by the modules.

- The chemistry modules of both PLUVUE and the ERT Visibility Model showed reasonable agreement between predictions and measurements of the NO_2/NO_x ratio, with consideration given to the uncertainties introduced by the dispersion module because of the dependence of plume chemistry upon plume dispersion.

- The PLUVUE optics module compares satisfactorily with the case studies. Average absolute relative errors in plume contrast are 47, 45, 39, and 164 percent at 405, 450, 550, and 630 nm, respectively. The evaluation of the PLUVUE optics module showed that the plume visual effects were overestimated in 9 out of the 10 case studies.

- The ERT optics module performance compares satisfactorily with the case studies. Average absolute relative errors in plume contrast are 46, 34, 21, and 51 percent at 405, 450, 550, and 630 nm, respectively. The ERT optics module underestimated plume visual effects in all 10 cases.

ORGANIZATION OF THE REPORT

First, an overview of the data base of the 1979 VISTTA field program used here for model evaluation and discussed briefly in terms of data uncertainties is presented in section 2. The statistical measures used to evaluate model performance are introduced in section 3. They include measures suggested by the American Meteorological Society (AMS) Workshop on Dispersion Model Performance (Fox, 1981) and some additional measures used by Bergstrom et al. (1981) in their evaluation of PLUVUE. Sections 4 and 5 present the results of the overall evaluations of PLUVUE and the ERT Visibility Model. The evaluation of the dispersion, chemistry, and optics modules of PLUVUE is presented in Appendix A. The evaluation of the dispersion, chemistry, and optics modules of the ERT Visibility Model is presented in Appendix B. A discussion of the sensitivity/uncertainty analysis of PLUVUE is presented in Appendix C. Modifications made to the ERT Visibility Model computer code for the purpose of carrying out the evaluation study are described in Appendix D.

SECTION 2

OVERVIEW OF THE DATA BASE

During the 1979 VISTTA field programs, an important data base was developed for evaluating plume visibility models. To evaluate a mathematical model such as PLUVUE or the ERT Visibility Model, however, consistent and reliable data that involve stable meteorological conditions and a fairly homogeneous background (e.g., clear sky, homogeneous cloud layer, mountain) must be selected.

For this evaluation, we considered five days during which plume and visibility measurements were obtained at downwind distances ranging from 4 to 31 km. Although data from other days could also have been analyzed, the five days chosen--28 June, 13 July, and 4, 7, and 15 December, 1979--appeared to offer the best data sets for plume visibility modeling. These case studies covered a wide range of conditions:

- On 28 June, good telephotometer measurements of the visual effects against a dark background--Navajo Mountain--were obtained.

- During the summer program, the best day for obtaining plume data with a clear sky was 13 July. Although the activities on that day were not designed for visibility evaluation, a flight path of the aircraft corresponded to two telephotometer plume targets.

- A stable plume was observed on 4 December, with a cloud layer in the background, that could be approximated in the model by a homogeneous light gray background.

- The data obtained on 7 December represent almost one-third of all the data available for optics module evaluation because meteorological conditions, which included a clear sky, were favorable.

- On 15 December, the darkest plume was observed, with a clear sky in the background.

The overall evaluations of the visibility models were carried out using those cases for which acceptable telephotometer measurements were made at the time of a flight:

- Flights 5 and 7 on 28 June.

- Flight 1 on 13 July (two telephotometer sites).

- Flights 2, 3, 4, 5, and 12 on 4 December.

- Flights 2, 3, 4, 7, 8, 9, 10, and 11 on 7 December (morning).

- Flights 1, 2, 3, 4, 5, and 7 on 7 December (afternoon).

- Flights 2, 3, 7, and 9 on 15 December.

Both PLUVUE and the ERT Visibility Model offer the possibility of calculating the visual effects of a plume against a homogeneous gray background of a given reflectance. The case studies of 28 June (dark gray background) and 4 December (light gray background) offer an interesting data base with which to evaluate this option. The photographs of the plume corresponding to the telephotometer measurements were used to

determine the reflectance of the background (cloud layer on Navajo Mountain). These photographs were compared with the photographs of the MacBeth colorchecker chart that corresponded to the same sets of measurements (Hudischewskyj et al., 1981). The reflectances of the gray from the colorchecker charts are available, and the following values were used:

> 28 June, Navajo Mountain background: Reflectance = 0.20

> 4 December, cloud layer background: Reflectance = 0.60.

From data concerning the observer location and sight path azimuth, the distance between the observer and Navajo Mountain was estimated to be about 63 km. Some uncertainty is associated with the distance between the observer and the cloud layer. A distance of 100 km was chosen, but the model did not appear to be very sensitive to that value unless it approached the visual range.

The evaluations of the diffusion modules and the chemistry and aerosol modules were carried out for the same cases as those used for the overall model evaluations. This technique allowed parallel evaluation of the dispersion modules and the chemistry and aerosol modules and, thus, the relative uncertainties introduced by the separate components of the visibility models could be estimated. In some cases (15 December--cases 3, 7, and 9), the telephotometer sight path was not perfectly aligned with the aircraft flight path; therefore, evaluations of the overall model and the optics modules were performed at different downwind distances from those for the diffusion modules and the chemistry and aerosol modules.

Plume widths were obtained from aircraft measurements by considering the variation in SO_2 concentrations. For this study, measured SO_2 concentrations above 20 ppb defined the plume. Corrections were made for variations in the altitude of the aircraft and for the angle between the plume centerline and the flight path. It should be noted, however, that

the use of SO_2 concentration measurements can lead to some uncertainty in the measured plume width because of the slow time response of the SO_2 monitor (Seigneur et al., 1981).

In addition to plume widths and plume centerline concentrations, concentrations integrated across the plume were also of interest because they provide an indirect measure of plume vertical dispersion. Moreover, the integrated plume concentrations of NO_2 and particles are of special interest because they are directly input to the optics modules. Thus, NO_2 concentrations and particle-scattering coefficient values integrated in the plume along the telephotometer sight path were also analyzed.

The optics modules were evaluated on the basis of the data obtained on 7 December. Because the input data required for these modules are plume width and plume concentrations integrated along the sight path through the plume center, it was necessary to choose aircraft flight paths that coincided with the telephotometer sight paths. For some flight paths, plume widths and concentrations measured by the aircraft were inconsistent with the bulk of the data. Such paths probably represent cases in which the aircraft flew through the top or bottom of the plume rather than through the plume center and these cases were not considered in the optics module evaluations. It should be noted that for the 10 cases selected, some uncertainties still exist because we assumed that the aircraft flight path and telephotometer sight path were exactly aligned and that the aircraft flight path moved through the plume centerline. An overview of the input data is shown in table 1.

TABLE 1. INPUT DATA FOR PLUVUE AND THE ERT PLUME VISIBILITY MODEL (1979)

Input Data	28 June	13 July	4 December	7 December	15 December
Emission rates (tons per day)					
SO_2	261.9	261.9	273.0	177.1	286.7
NO_x	108.9	108.9	127.7	97.4	124.7
Primary particulates	22.0	22.0	16.1	8.4	18.04
Meteorological data					
Wind speed ($m \cdot sec^{-1}$)	1.3-3.6	3.0	1.5-2.5	2.0-2.4	2.6
Wind direction (°)	246-290	295.0	81.0-123.1	79.0-127.0	122.0
Ambient temperature (K)	299.2	298.1	284.7	277.6-284.7	278.7-279.3
Stability class	E	D	E	E	E
Relative humidity (%)	45.0	16.0	45.0	36.0-67.0	27-32
Background ozone (ppm)	0.034	0.044	0.034	0.031-0.037	0.037-0.03
Visual range (km)	177.1	183.6	228.2	274.2-292.0	260.0
Downwind distances (km)	12.0-28.0	28.7	9.3-24.8	4.25-22.5	11.5-31.3
Measurement time (MST)	0726-0845	0706	0934-1241	0908-1540	1125-1236

SECTION 3

PERFORMANCE MEASURES

After the independent evaluations of each of the individual modules and the overall evaluations of PLUVUE and of the ERT Visibility Model were conducted, several model outputs were considered in the performance evaluation procedure:

> Plume/sky intensity ratios, plume contrasts, and blue/red ratios for the overall model evaluation and for the optics module evaluation:

- The plume/sky intensity ratios is defined as $I^p(\lambda)/I^s(\lambda)$, where λ is the wavelength, $I^p(\lambda)$ is the light intensity at the plume centerline, and $I^s(\lambda)$ is the light intensity of the background intensity at the same elevation angle as if the plume were not present. As previously mentioned, the wavelengths used in the telephotometer measurements of light intensity were 405, 450, 550, and 630 nm; PLUVUE model predictions are performed at 39 wavelengths ranging from 370 to 750 nm and model predictions can therefore be obtained for the four telephotometer wavelengths. The wavelengths used in the ERT Visibility Model are 400, 450, 550, and 650 nm.

- Plume contrast is related to the plume/sky intensity ratio and is defined as follows:

$$C(\lambda) = \frac{I^p(\lambda) - I^s(\lambda)}{I^s(\lambda)} \quad . \qquad (1)$$

- The blue/red ratio is a measure of plume discoloration and is defined from the plume/sky intensity ratio in the blue and red wavelengths:

$$\text{Blue/Red Ratio} = \frac{I^p(450\text{ nm}) \cdot I^s(630 \text{ or } 650\text{ nm})}{I^s(450\text{ nm}) \cdot I^p(630 \text{ or } 650\text{ nm})} \quad . \qquad (2)$$

  A ratio of less than one characterizes a reddish plume, whereas a ratio greater than one characterizes a bluish plume.

> Plume width for the dispersion module evaluation.

> The concentration of NO_x at the plume centerline for the dispersion module evaluation.

> The ratio of NO_2 to NO_x concentration at the plume centerline for the chemistry module evaluation. (This ratio is also affected by plume dispersion.)

> Integrated NO_2 concentrations and b_{sp} (550 nm) values along the line of sight, where b_{sp} is the scattering coefficient of particulate matter at 550 nm. This formulation can be used to evaluate dispersion module performance.

The statistical performance measures recommended for air quality model evaluation by the American Meteorological Society Workshop (Fox, 1981) were used to evaluate the performance of PLUVUE and the ERT Visibility Model. These measures, which include the Pearson correlation coefficient, systematic bias and variance of differences, gross error and confidence interval, and root-mean-square error, are discussed in the

remainder of this section. Their appropriateness for air quality model evaluation has been discussed elsewhere by Fox (1981).

The correlation coefficient r is defined as follows:

$$r = \frac{\sum_{i=1}^{N} (X_{i,m} - \bar{X}_m)(X_{i,p} - \bar{X}_p)}{\left[\sum_{i=1}^{N} (X_{i,m} - \bar{X}_m)^2 \cdot \sum_{i=1}^{N} (X_{i,p} - \bar{X}_p)^2\right]^{1/2}} \quad , \tag{3}$$

where $X_{i,m}$ and $X_{i,p}$ are the measured and predicted values of some model output (e.g., plume contrast) for case study i, $\bar{X}_m$ and $\bar{X}_p$ are the average measured and predicted values, and N is the total number of case studies considered in the model performance evaluation.

Bias is defined as the average value of the differences between measured and predicted values:

$$\bar{d} = \frac{1}{N} \sum_{i=1}^{N} (X_{i,m} - X_{i,p}) \quad , \tag{4}$$

The confidence interval for the bias can be constructed from Student's t distribution:

$$\pm t_\nu \left(\frac{S_o^2}{N} + \frac{S_p^2}{N}\right)^{1/2} \quad , \tag{5}$$

where t_ν is Student's t-statistic with ν degrees of freedom, S_o^2 is the estimated variance of the observations, and S_p^2 is the estimated variance of the predictions.

The variance of the distribution of differences is defined as follows:

$$S_d^2 = \frac{1}{N-1} \sum_{i=1}^{1} \left[(X_{i,m} - X_{i,p}) - (\overline{X}_{i,m} - \overline{X}_{i,p}) \right]^2 \quad , \qquad (6)$$

The confidence interval for the true variance, σ_d^2, is given by

$$\frac{\nu S_d^2}{\chi^2_{\nu,\ 1-x}} < \sigma_d^2 < \frac{\nu S_d^2}{\chi^2_{\nu,\ x}} \quad , \qquad (7)$$

where $\chi^2_{\nu,\ x}$ is the x^{th} percentile of the chi-square distribution for ν degrees of freedom.

The gross error is defined as the average value of the absolute values difference between measured and predicted values:

$$GE = \frac{1}{N} \sum_{i=1}^{N} |X_{i,\ m} - X_{i,p}| \quad . \qquad (8)$$

The root-mean-square error is defined as the square root average value of the square of the differences between measured and predicted values:

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^{N} |X_{i,\ m} - X_{i,\ p}|^2 \right]^{1/2} \quad . \qquad (9)$$

In addition to the statistical performance measures recommended by the AMS workshop, several additional statistical performance measures were computed that are of interest for this analysis. A linear regression analysis of the measured and predicted values that were considered yields,

in addition to the correlation coefficient, the equation of the line of regression between these measured and predicted values. This line of regression is characterized by its slope and its intercept on the ordinate axis. A perfect regression has a slope of one and an intercept value of zero.

To quantify model performance in predicting plume contrast, plume/sky intensity ratios, and blue/red ratio, four additional performance measures were also defined: The average absolute relative error of the plume/sky intensity ratios, E_1, and the average signed relative error of the plume/sky intensity ratios, S_1, are given in equations (10) and (11), respectively:

$$E_1(\lambda) = \frac{1}{N} \sum_{i=1}^{N} \left| \frac{\left(\frac{I^P}{I^S}\right)_{i,\,\text{Measured}} - \left(\frac{I^P}{I^S}\right)_{i,\,\text{Predicted}}}{\left(\frac{I^P}{I^S}\right)_{i,\,\text{Measured}}} \right| , \qquad (10)$$

$$S_1(\lambda) = \frac{1}{N} \sum_{i=1}^{N} \frac{\left(\frac{I^P}{I^S}\right)_{i,\,\text{Measured}} - \left(\frac{I^P}{I^S}\right)_{i,\,\text{Predicted}}}{\left(\frac{I^P}{I^S}\right)_{i,\,\text{Measured}}} , \qquad (11)$$

where I^P/I^S is the plume/sky intensity ratio, which depends on the wavelength λ, and N is the number of comparisons. The absolute and signed average relative errors of the contrast are defined by equations (12) and (13), respectively:

$$E_2(\lambda) = \frac{1}{N} \sum_{i=1}^{N} \left| \frac{C_{i,\,\text{Measured}} - C_{i,\,\text{Predicted}}}{C_{i,\,\text{Measured}}} \right| , \qquad (12)$$

$$S_2(\lambda) = \frac{1}{N} \sum_{i=1}^{N} \frac{(C_{i,\,\text{Measured}} - C_{i,\,\text{Predicted}})}{C_{i,\,\text{Measured}}} \quad , \tag{13}$$

where C_i is the contrast, defined as

$$C_i = \frac{I_i^P - I_i^S}{I_i^S} \quad . \tag{14}$$

These measures were calculated for the cases in which the measured contrast was greater in absolute value than 0.02, which corresponds to the accepted value for the contrast threshold (Friedlander, 1977).

It should be noted that the performance measures $S_1(\lambda)$ and $S_2(\lambda)$ have the opposite sign of those presented in the performance evaluation of PLUVUE by Bergstrom et al. (1981). This occurs because the definitions of $S_1(\lambda)$ and $S_2(\lambda)$ were chosen to be consistent with the definition of the bias recommended by the AMS Workshop (Fox, 1981).

Plume/sky intensity ratio is a characteristic of the telephotometer measurements, whereas contrast is perceived by the human eye. The performance measures E_1 and S_1 are therefore representative of how well the model prediction compares with measurements, whereas the performance measures E_2 and S_2 represent the ability of the model to predict a visual effect such as contrast. The measures $E_1(\lambda)$ and $E_2(\lambda)$ can be defined as gross errors when the difference between measured and predicted values are normalized with respect to the measured values, whereas the measures $S_1(\lambda)$ and $S_2(\lambda)$ can be defined as bias when the differences are normalized with respect to the measured values.

SECTION 4

OVERALL EVALUATION OF PLUVUE

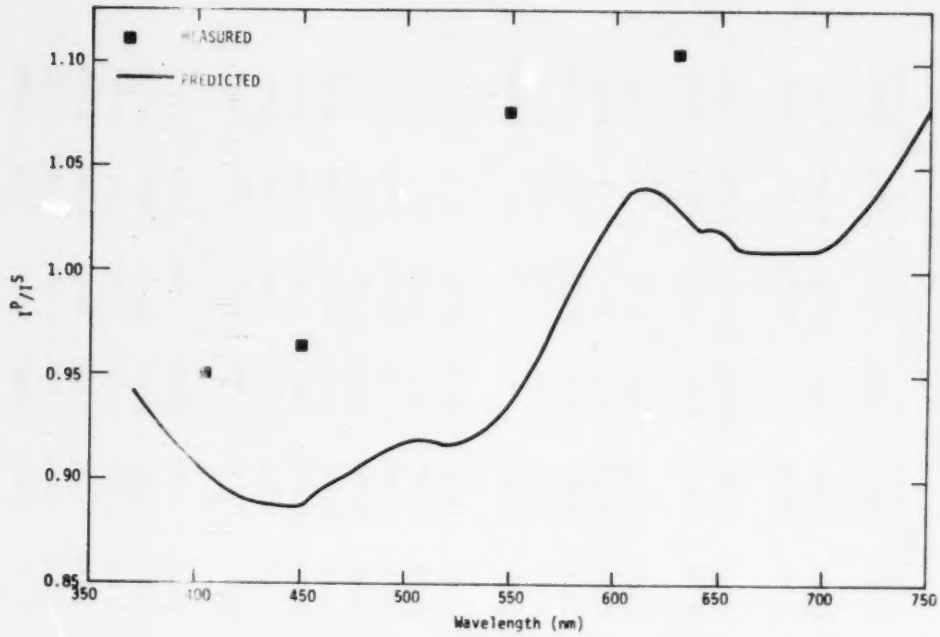
The data base used in this model evaluation includes cases exhibiting clear-sky, dark-mountain, and hazy-sky backgrounds. PLUVUE simulations can be conducted with or without an object in the background. Blue-sky case studies were simulated using the model option of sky background (i.e., no background object). The dark-mountain background was simulated by including a dark object having a reflectance of 20 percent. The hazy-sky background was simulated by including a white object having a reflectance of 60 percent.

Results of the model evaluation are presented in table 2. The data listed in the table include the date and time of measurement, the downwind distance of the plume target from the source, the plume-observer distance, the background conditions, and the plume/sky intensity ratio predicted by the model and measured by the telephotometer. Model predictions are conducted at 39 wavelengths, with increments of 10 nm. Results are shown at the four telephotometer wavelengths mentioned earlier: 405, 450, 550, and 630 nm. Model predictions at 405 nm were interpolated from predictions performed at 400 and 410 nm. The measured and predicted plume/background intensity ratios of typical case studies--one for each set of measurements taken over a day or a half-day--are shown in figure 1. In general, the model overpredicts the reduction in light intensity caused by the plume.

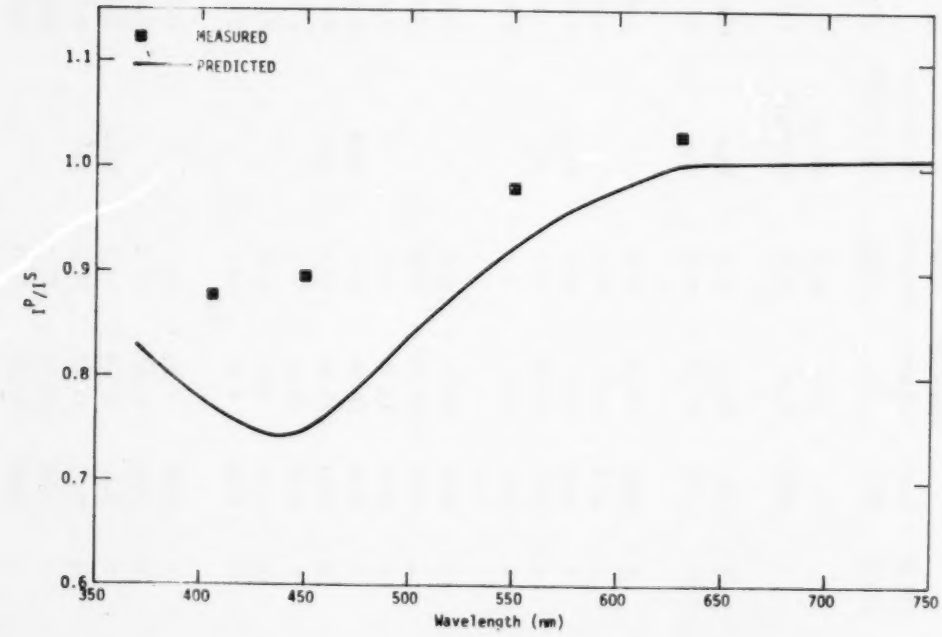
For the case studies of 28 June 1979, when the plume is viewed against a dark background, the model underpredicts the plume/background intensity ratio in all cases. However, large uncertainties in the plume

TABLE 2. COMPARISON OF MEASURED AND PREDICTED PLUME/SKY INTENSITY RATIOS FOR THE OVERALL EVALUATION OF PLUVUE

Day (1979)	Flight Number	Time (MST)	Downwind Distance (km)	Observed Plume Distance (km)	Background Conditions	IP/IS (nm) 405 Mea.	405 Pred.	450 Mea.	450 Pred.	550 Mea.	550 Pred.	630 Mea.	630 Pred.
28 June	5	0726	11.5	26.2	Navajo	0.950	0.905	0.963	0.892	1.076	0.948	1.103	1.06
	7	0845	28.0	46.2	Mountain	1.20	0.959	1.26	0.916	1.41	0.894	1.50	0.906
13 July	1-LR	0706	28.70	15.1	Blue	0.875	0.769	0.895	0.746	0.980	0.926	1.030	1.009
	1-KC	0706	28.70	19.4	sky	0.935	0.879	0.945	0.860	0.995	0.927	0.995	0.960
4 December	2	0934	9.25	13.1		0.88	0.680	0.87	0.647	0.94	0.761	0.98	0.806
	3	0951	16.5	11.7		0.86	0.684	0.86	0.667	0.95	0.817	0.98	0.869
	4	1008	19.5	13.9	Hazy	0.88	0.730	0.83	0.709	0.90	0.838	0.98	0.880
	5	1042	24.75	21.2	sky	0.86	0.845	0.85	0.814	0.96	0.880	0.96	0.908
	12	1241	15.0	22.0		0.89	0.865	0.90	0.841	0.97	0.891	0.97	0.906
7 December	2	0908	21.25	18.9		0.933	0.817	0.905	0.798	0.939	0.897	0.969	0.936
(morning)	3	0929	21.25	16.0		0.925	0.794	0.926	0.781	0.942	0.893	0.973	0.936
	4	0949	11.75	11.7		0.894	0.787	0.915	0.781	0.934	0.878	0.946	0.920
	7	1030	20.80	17.7	Blue	0.902	0.804	0.899	0.786	0.942	0.888	0.985	0.930
	8	1044	21.50	19.0	sky	0.890	0.805	0.876	0.785	0.935	0.885	1.000	0.929
	9	1107	14.00	14.8		0.873	0.817	0.905	0.807	0.942	0.897	0.988	0.932
	10	1135	9.30	20.4		0.900	0.851	0.881	0.830	0.927	0.893	0.979	0.924
	11	1154	4.30	16.3		0.819	0.832	0.779	0.809	0.860	0.859	0.959	0.893
7 December	1	1409	7.75	16.5		0.830	0.869	0.844	0.854	0.925	0.908	0.969	0.932
(afternoon)	2	1427	12.00	16.6		0.830	0.858	0.810	0.843	0.925	0.903	0.975	0.932
	3	1438	12.50	11.9	Blue	0.851	0.825	0.818	0.818	0.919	0.894	0.981	0.927
	4	1459	17.00	14.6	sky	0.848	0.823	0.819	0.791	0.925	0.847	0.983	0.890
	5	1505	22.50	27.8		0.940	0.855	0.940	0.816	0.930	0.882	1.000	0.923
	7	1540	22.00	26.3		0.773	0.846	0.777	0.801	0.863	0.866	0.976	0.908
15 December	2	1125	17.70	14.1		0.882	0.702	0.893	0.676	0.991	0.868	0.937	0.974
	3	1133	11.50	20.2	Blue	0.758	0.843	0.887	0.815	0.951	0.870	0.984	0.89
	7	1209	30.50	32.6	sky	0.819	0.857	0.837	0.803	0.920	0.846	0.962	0.892
	9	1236	31.30	33.2		0.806	0.860	0.828	0.805	0.883	0.844	0.969	0.893

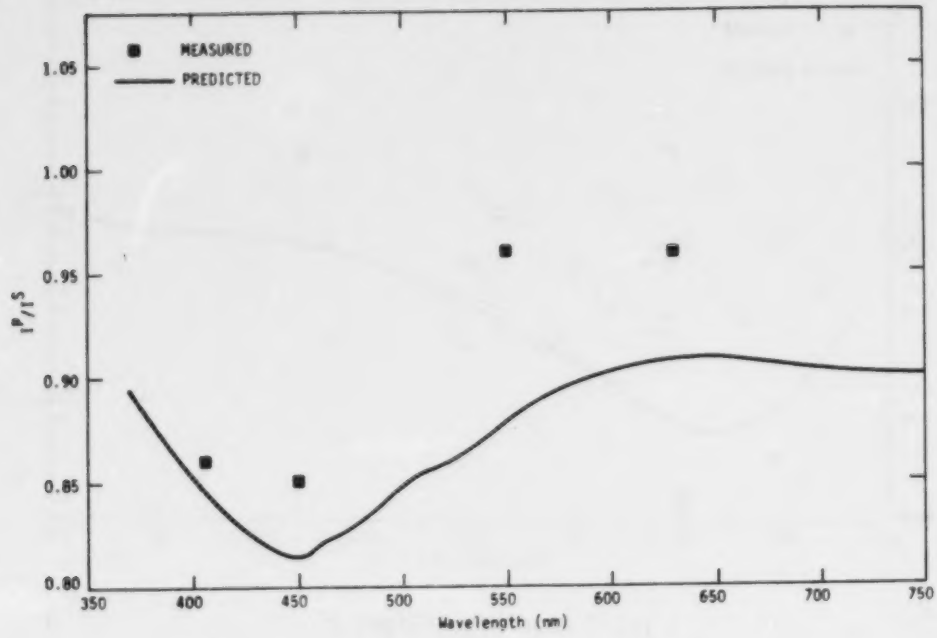


(a) 28 June, Flight 5

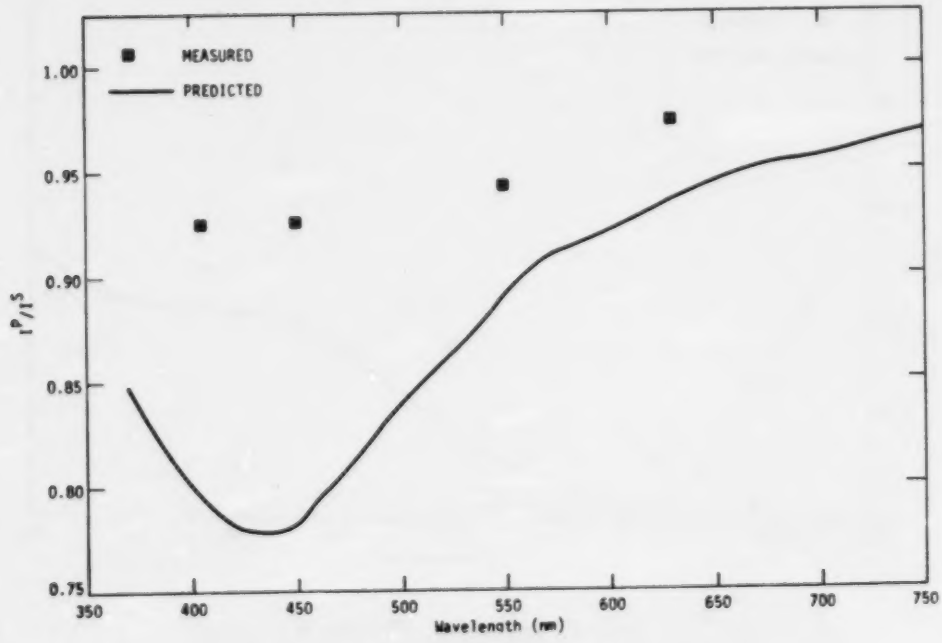


(b) 13 July, Flight 1 (Observer-Plume Distance = 15.1 km)

Figure 1. Comparison of measured and predicted plume/sky intensity ratios for the overall evaluation of PLUVUE--1979.

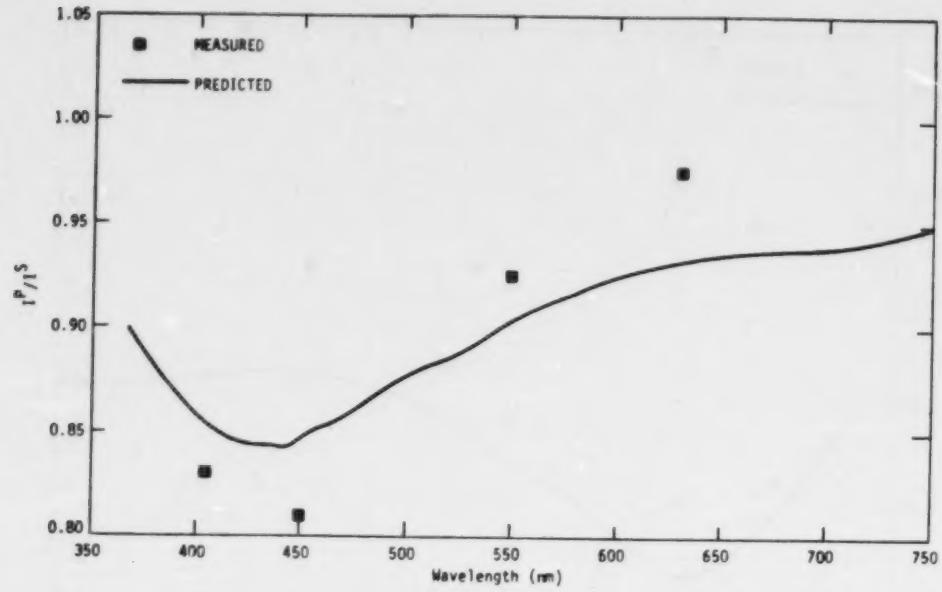


(c) 4 December, Flight 5

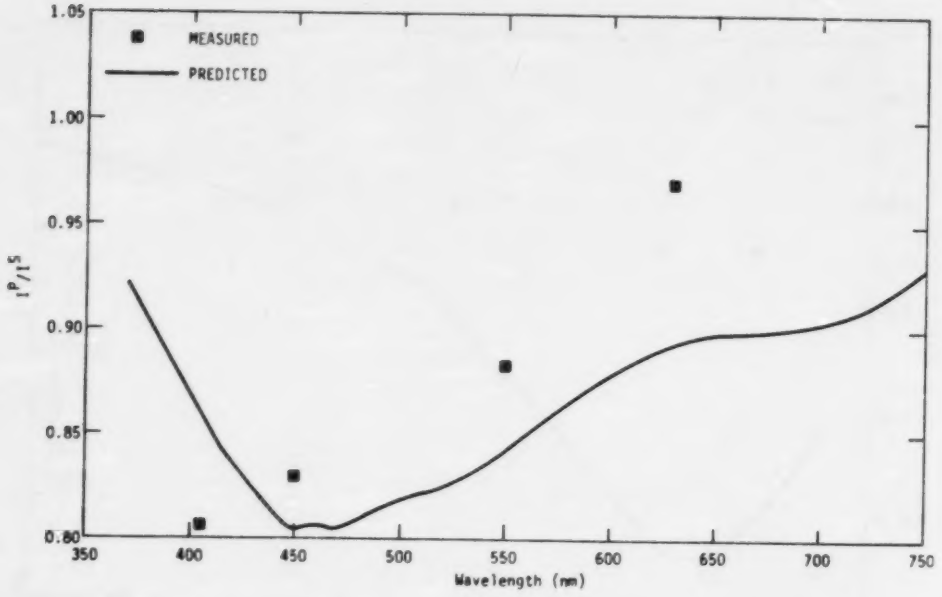


(d) 7 December, Morning Flight 3

Figure 1 (Continued).



(e) 7 December, Flight 2



(f) 15 December, Flight 9

Figure 1 (Concluded).

NO_2 and particulate integrated concentrations make a detailed evaluation of the model difficult. It should be noted that the negative contrast of the plume at short wavelengths (400 and 450 nm) and the positive contrast at higher wavelengths (e.g., 650 nm) are well predicted by the model for case 5 [see figure 1(a)].

The case studies of 13 July 1979 show an overprediction of the plume visual effects, especially at shorter wavelengths. This results mainly from the overestimation of the formation rate of NO_2 for this plume simulation.

The case studies of 4 December 1979 correspond to plume intensity measurements taken against a cloudy background. The model overpredicts the plume visual effects in all cases. The approximation of the cloud layer by a homogeneous light gray background in the model seems to be the main source of uncertainty, because the model components--the diffusion and chemistry modules--perform as well as for the other days.

For the case studies of the morning of 7 December 1979, the model shows a general trend toward overestimating the plume visual effects; model performance, however, is better than for the cases of 4 December. Excellent agreement is obtained for the cases of the afternoon of 7 December 1979 [see figure 1(e)]. This result is consistent with the good performance of the optics module and of the chemistry module (see Appendix A).

The model predictions also agree well with the measurements for the four case studies of 15 December 1979. This day corresponds to a stable dark plume against a clear sky, and it appears that the plume visibility model is able to predict plume visual effects well under such conditions.

Performance measures for the PLUVUE overall evaluation are presented in tables 3, 4, and 5 for cases under clear-sky, dark-mountain, and hazy-sky background conditions, respectively. Statistical performance measures for the 2 case studies under dark-mountain background conditions (table 4)

TABLE 3. PLUVUE PERFORMANCE ANALYSIS OF 20 CASE STUDIES UNDER CLEAR-SKY BACKGROUND CONDITIONS

Performance Measure	Plume/Sky Intensity Ratios; Plume Contrasts* (Wavelength--nm) 405	450	550	630	Blue/Red Ratio
Linear Regression					
Measured mean value	0.86	0.87	0.93	0.98	0.89
Predicted mean value	0.82	0.80	0.90	0.93	0.86
Correlation coefficient	-0.263	-0.153	0.619	0.366	-0.392
Slope	-0.340	-0.199	0.360	0.251	-0.355
Intercept	1.140	1.030	0.609	-0.754	1.20
Residual Statistics					
Bias	+0.039	+0.069	+0.035	+0.051	0.025
Bias confidence interval	±0.026	±0.025	±0.027	±0.014	±0.030
Variance	0.006	0.005	0.002	0.0008	0.008
True variance confidence interval	0.004-0.0011	0.003-0.009	0.001-0.004	0.0005-0.0016	0.005-0.016
Root-mean-square error	0.084	0.095	0.057	0.059	0.092
Normalized Residual Statistics					
E_1	0.083	0.088	0.054	0.056	0.084
S_1†	+0.041	+0.070	+0.053	+0.052	0.023
E_2†	0.690	0.833	0.691	1.539	--
S_2†	-0.528	-0.784	-0.689	-1.325	--

* Linear regression and nonnormalized residual statistics are listed for the plume/sky intensity ratios; normalized residual statistics E_1 and S_1 correspond to plume/sky intensity ratios, and E_2 and S_2 refer to plume contrasts.

† Cases showing measured absolute plume contrast of less than 0.02 were discarded from the calculation; the total number of cases were 20, 20, 17, and 12 at 405, 450, 550, and 630 nm, respectively.

TABLE 4. PLUVUE PERFORMANCE ANALYSIS OF 2 CASE STUDIES UNDER DARK-MOUNTAIN BACKGROUND CONDITIONS--NORMALIZED RESIDUAL STATISTICS

Performance Measure	Plume/Sky Intensity Ratios; Plume Contrasts* (Wavelength--nm) 405	450	550	630	Blue/Red Ratio
Measured mean value	1.075	1.112	1.243	1.301	0.856
Predicted mean value	0.932	0.904	0.921	0.983	0.926
E_1	0.124	0.174	0.243	0.218	0.120
S_1	+0.124	+0.174	+0.243	+0.218	-0.084
E_2	1.053	1.621	7.135	0.803	--
S_2	+0.153	-0.298	7.135	0.803	--

TABLE 5. PLUVUE VISIBILITY MODEL PERFORMANCE ANALYSIS OF 5 CASE STUDIES UNDER HAZY-SKY BACKGROUND CONDITIONS--NORMALIZED RESIDUAL STATISTICS

Performance Measure	Plume/Sky Intensity Ratios; Plume Contrasts* (Wavelength--nm) 405	450	550	630	Blue/Red Ratio
Measured mean value	0.874	0.862	0.944	0.974	0.89
Predicted mean value	0.761	0.736	0.837	0.874	0.84
E_1	0.129	0.147	0.113	0.103	0.0588
S_1	+0.129	0.147	0.113	0.103	-0.0544
E_2	0.902	0.927	2.179	1.717	--
S_2	-0.902	-0.927	-2.179	-1.717	--

* E_1 and S_1 correspond to plume/sky intensity ratios, and E_2 and S_2 refer to plume contrasts.

and the 5 case studies under hazy-sky background conditions (table 5) were limited to normalized residual statistics because of the relatively small number of case studies conducted. The statistical performance measures for the case studies under clear-sky background conditions are of the greatest value because they involve a larger number of cases--20 studies--and the simulations did not involve any background object.

The correlation coefficient for measured and predicted values for the overall model evaluation under clear-sky background conditions is negative in the blue light range-- -0.263 and -0.153 at 405 and 450 nm, respectively; average (0.619) at 550 nm, and low (0.366) at 630 nm. A negative correlation coefficient (-0.392) is calculated for the blue/red ratio. This poor overall performance of PLUVUE can, at this point, be attributed to any of the modules (dispersion, or chemistry, or optics). Uncertainties in the model input data could also affect model performance; however, it is unlikely that this is the main cause of poor model performance. The sensitivity of PLUVUE to uncertainties in the input data is analyzed in Appendix C.

The average absolute normalized error values in plume/sky intensity ratios are 8.3, 8.8, 5.4, and 5.6 percent at 405, 450, 550, and 630 nm, respectively. The average absolute normalized error values in plume contrast are 69, 83, 69, and 159 percent at the four wavelengths. From the values of the signed deviations in plume/sky intensity ratio and plume contrast, it appears that PLUVUE overestimates the plume visual effects at all wavelengths, on the average.

Only two cases under dark-mountain background conditions were available, an insufficient number for calculating sound statistical measures. Thus, only E_1, S_1, E_2, and S_2 were calculated. From these results (shown in table 4), model performance appears to be poor. From the data presented in table 2, it appears that for case 5, the plume was darker in the blue light range and brighter in the green and red, whereas for case 7, a bright plume was observed at all wavelengths. PLUVUE predicts a brighter plume for case 5 at 630 nm only.

Five case studies under hazy background conditions were available for model evaluation and, therefore, only E_1, S_1, E_2, and S_2 were calculated (table 5). Model performance is poor, perhaps partly because of the approximation of the haze by a light gray reflector.

SECTION 5

OVERALL EVALUATION OF THE ERT VISIBILITY MODEL

The data base for this model evaluation includes 20 cases under clear-sky, 2 cases under dark-mountain, and 5 cases under hazy-sky background conditions. The cases having clear-sky backgrounds were simulated by placing the background object beyond the visual range. The dark-mountain background was simulated by placing a dark object having a reflectance of 20 percent at an inclination of 60°. The hazy-sky background was approximated by a white object having a reflectance of 60 percent placed vertically at 100 km from the observer.

The results of the 27 simulations are presented in table 6. The date and time of the measurement, the downwind distance of the plume target from the source, the plume-observer distance, and the background conditions are listed, along with the plume/sky intensity ratio predicted by the model and measured by multiwavelength telephometers at four wavelengths. The ERT Visibility Model predictions were carried out at 400, 450, 550, and 650 nm. Model performance is described in tables 7, 8, and 9 for cases under clear-sky, dark-mountain, and hazy-sky backgrounds conditions, respectively. Statistical performance measures for the 2 case studies involving dark-moutain backgrounds (table 8) and the 5 case studies involving hazy-sky backgrounds (table 9) were limited to normalized residual statistics, again because of the relatively small number of case studies conducted. The case studies having clear-sky backgrounds are of the greatest interest because they do not involve background objects and, therefore, they can more easily be simulated by a plume visibility model.

TABLE 6. COMPARISON OF MEASURED AND PREDICTED PLUME/SKY INTENSITY RATIOS FOR THE OVERALL EVALUATION OF THE ERT VISIBILITY MODEL

Day (1979)	Flight Number	Time (MST)	Downwind Distance (km)	Observer Plume Distance (km)	Background Conditions	IP/IS (nm) 405 Mea.	405 Pred.	450 Mea.	450 Pred.	550 Mea.	550 Pred.	630 Mea.	630 Pred.
28 June	5	0726	11.5	26.2	Navajo	0.950	0.881	0.963	0.973	1.076	1.319	1.103	1.692
	7	0845	28.0	46.2	Mountain	1.20	0.720	1.26	0.748	1.41	0.976	1.50	1.182
13 July	1-LR	0706	28.70	15.1	Blue sky	0.875	0.886	0.895	0.901	0.980	1.083	1.030	1.277
	1-KC	0706	28.70	19.4		0.935	0.919	0.945	0.911	0.995	0.973	0.995	1.037
4 December	2	0934	9.25	13.1		0.88	0.825	0.87	0.778	0.94	0.673	0.98	0.598
	3	0951	16.5	11.7		0.86	0.841	0.86	0.771	0.95	0.644	0.98	0.594
	4	1008	19.5	13.9	Hazy sky	0.88	0.847	0.83	0.778	0.90	0.644	0.98	0.622
	5	1042	24.75	21.2		0.86	0.861	0.85	0.799	0.96	0.715	0.96	0.688
	12	1241	15.0	22.0		0.89	0.874	0.90	0.809	0.97	0.705	0.97	0.671
7 December (morning)	2	0908	21.25	18.9	Blue sky	0.933	0.932	0.905	0.914	0.939	0.937	0.969	0.998
	3	0929	21.25	16.0		0.925	0.933	0.926	0.915	0.942	0.942	0.973	1.001
	4	0949	11.75	11.7		0.894	0.933	0.915	0.917	0.934	0.956	0.946	1.041
	7	1030	20.80	17.7		0.902	0.936	0.899	0.919	0.942	0.947	0.985	1.005
	8	1044	21.50	19.0		0.890	0.935	0.876	0.918	0.935	0.946	1.000	1.004
	9	1107	14.00	14.8		0.873	0.942	0.905	0.927	0.942	0.954	0.988	1.018
	10	1135	9.30	20.4		0.900	0.939	0.881	0.922	0.927	0.945	0.979	1.012
	11	1154	4.30	16.3		0.819	0.914	0.779	0.892	0.860	0.926	0.959	1.033
7 December (afternoon)	1	1409	7.75	16.5	Blue sky	0.830	0.949	0.844	0.934	0.925	0.951	0.969	0.999
	2	1427	12.00	16.6		0.830	0.952	0.810	0.939	0.925	0.958	0.975	1.003
	3	1438	12.50	11.9		0.851	0.948	0.818	0.935	0.919	0.961	0.981	1.013
	4	1459	17.00	14.6		0.848	0.948	0.819	0.936	0.925	0.963	0.983	1.013
	5	1505	22.50	27.8		0.940	0.933	0.940	0.916	0.930	0.946	1.000	0.998
	7	1540	22.00	26.3		0.773	0.928	0.777	0.911	0.863	0.943	0.976	1.004
15 December	2	1125	17.70	14.1		0.882	0.908	0.893	0.943	0.991	1.252	0.937	1.738
	3	1133	11.50	20.2	Blue sky	0.758	0.932	0.887	0.913	0.951	0.924	0.984	0.979
	7	1209	30.50	32.6		0.819	0.905	0.837	0.882	0.920	0.908	0.962	0.968
	9	1236	31.30	33.2		0.806	0.904	0.828	0.881	0.883	0.908	0.969	0.969

TABLE 7. ERT VISIBILITY MODEL PERFORMANCE ANALYSIS OF 20 CASE STUDIES UNDER CLEAR-SKY BACKGROUND CONDITIONS

Performance Measure	Plume/Sky Intensity Ratios; Plume Contrasts* (Wavelength--nm) 405	450	550	630	Blue/Red Ratio
Linear Regression					
Measured mean value	0.86	0.87	0.93	0.98	0.89
Predicted mean value	0.93	0.92	0.97	1.06	0.88
Correlation coefficient	0.066	0.099	0.587	-0.243	-0.241
Slope	0.200	0.292	0.271	-0.0284	-0.132
Intercept	-0.122	-0.107	-0.059	-0.020	1.01
Residual Statistics					
Bias	-0.0647	-0.0473	-0.0348	-0.0775	0.0062
Bias confidence interval	±0.0217	±0.0209	±0.0324	±0.0673	±0.0414
Variance	0.0030	0.0028	0.0039	0.0320	0.0138
True variance confidence interval	0.0019-0.0057	0.0017-0.0052	0.0024-0.0073	0.0201-0.060	0.0087-0.0259
Root-mean-square error	0.084	0.07	0.07	0.19	0.115
Normalized Residual Statistics					
E_1	0.082	0.065	0.044	0.081	+0.085
S_1	-0.079	-0.058	-0.037	-0.081	+0.002
E_2†	0.424	0.370	0.299	2.622	--
S_2†	+0.378	+0.253	+0.213	+1.250	--

* Linear regression and nonnormalized residual statistics are listed for the plume/sky intensity ratios; normalized residual statistics E_1 and S_1 correspond to plume/sky intensity ratios, whereas E_2 and S_2 refer to plume contrasts.

† Cases with measured absolute plume contrast of less than 0.02 were discarded from the calculation; the total number of cases were 20, 20, 17, and 12 at 405, 450, 550, and 630 nm, respectively.

TABLE 8. ERT VISIBILITY MODEL PERFORMANCE ANALYSIS OF 2 CASE STUDIES UNDER DARK-MOUNTAIN BACKGROUND CONDITIONS--NORMALIZED RESIDUAL STATISTICS

Performance Measure	Plume/Sky Intensity Ratios; Plume Contrasts* (Wavelength--nm)† 405	450	550	630	Blue/Red Ratio
Measured mean value	1.045	1.112	1.243	1.302	0.857
Predicted mean value	0.801	0.861	1.148	1.437	0.604
E_1	0.237	0.208	0.267	0.373	0.294
S_1	+0.237	-0.198	+0.041	-0.161	0.294
E_2	0.945	1.120	2.128	3.177	--
S_2	+0.51	+1.120	-1.069	-2.541	--

TABLE 9. ERT VISIBILITY MODEL PERFORMANCE ANALYSIS OF 5 CASE STUDIES UNDER HAZY-SKY BACKGROUND CONDITIONS--NORMALIZED RESIDUAL STATISTICS

Performance Measure	Plume/Sky Intensity Ratios; Plume Contrasts* (Wavelength--nm)† 405	450	550	630	Blue/Red Ratio
Measured mean value	0.874	0.862	0.944	0.974	0.885
Predicted mean value	0.850	0.787	0.680	0.635	1.234
E_1	0.028	0.087	0.279	0.348	0.406
S_1	+0.028	+0.087	+0.279	+0.348	-0.406
E_2	0.204	0.58	5.578	8.384	--
S_2	-0.201	-0.58	-5.578	-8.384	--

* E_1 and S_1 correspond to plume/sky intensity ratios, and E_2 and S_2 refer to plume contrasts.

The correlation coefficient for measured and predicted values for the overall model evaluation under clear-sky background is very low in the blue light range--0.066 and 0.099 at 405 and 450 nm, respectively; average (0.587) at 550 nm, and negative (-0.243) at 630 nm. These results suggest that there is little overall correlation between telephotometer measurements and model predictions. This lack of correlation can be caused by various components of the model, i.e., the treatment of dispersion, chemistry, or optics, or any combination of these elements. A negative correlation coefficient of -0.241 is calculated for the blue/red ratio.

Other statistical performance measures of particular interest are the bias and gross errors. We discuss here the values of the normalized bias (S_1 and S_2) and gross errors (E_1 and E_2), though this type of analysis could be applied to the normalized statistics as well. The average absolute normalized errors in plume/sky intensity ratios are 8.2, 6.5, 4.4, and 8.1 percent at 405, 450, 550, and 630 nm respectively. These values are comparable to the performance values of the PLUVUE, which were calculated to be 8.3, 8.8, 5.4, and 5.6 percent at these same wavelengths. The average absolute normalized errors in plume contrast are 42, 37, 30, and 262 percent at 405, 450, 550, and 630 nm, respectively. For comparison, the errors in plume contrast for PLUVUE were 69, 83, 69, and 154 percent at these same wavelengths.

It appears from the values of the bias that for clear-sky background cases, the ERT Visibility Model tends to underpredict plume visual effects, whereas PLUVUE tends to overpredict these effects. To determine the cause of the overall behavior of the ERT Visibility Model, it is necessary to individually evaluate the dispersion, chemistry, and optics modules.

Only two cases having dark-mountain backgrounds were studied--too few to provide much statistical information regarding model performance under these conditions. However, it is of interest to qualitatively evaluate the capability of the model to reproduce the main characteristics of the telephotometer measurements. The values for performance measures E_1, S_2,

E_2, and S_2 are presented in table 8 and for these two case studies, model performance is poor. A primary source of uncertainty in these simulations is the reflectance of the background object. The model shows good results for case study 5, predicting a darker plume at 400 and 450 nm and a brighter plume at 550 and 650 nm, both results that are in qualitative agreement with the measurements. Agreement is not as good for case study 7, for which a brighter plume was measured but a darker plume was predicted at all wavelengths except 630 nm.

For the overall evaluation, 5 case studies corresponded to hazy-sky background conditions--also an insufficient number with which to obtain much statistical information regarding model performance. The values for performance measures E_1, S_1, E_2, and S_2 were calculated and are presented in table 9. The poor model performance indicated in the table is probably caused in part by the use of a light gray reflector to simulate the background haze layer.

APPENDIX A

EVALUATION OF THE MODULES OF PLUVUE

A.1 EVALUATION OF THE DIFFUSION MODULE

The diffusion module of the plume visibility model is based on a Gaussian formulation of the dispersion of nonreactive pollutants. Several options are available for defining the horizontal and vertical dispersion coefficients: the stability class can be specified and the coefficients can then be computed from the Pasquill-Gifford-Turner (PGT) or the TVA dispersion curves; or the dispersion coefficients can be specified directly at specific downwind distances.

The dispersion curves of PGT have been deduced from empirical correlations of experimental data obtained from a release of tracers near ground level over flat terrain. Thus, one should not expect these empirical formulas to hold for elevated emission sources over complex terrain. However, since the PGT dispersion coefficients are likely to be used when plume visibility simulations are performed to assess the possible impact of new power plants or smelters on atmospheric visibility, it is of interest to present a brief comparison of the PGT dispersion estimates with the measurements obtained for the plume of the Navajo Generating Station.

Plume widths can be obtained from aircraft measurements by considering the variation in SO_2 concentrations. For this study, measured SO_2 concentrations above 20 ppb defined the plume. Corrections were made for variations in the altitude of the aircraft and for the angle between the plume centerline and the flight path. A comparison of the plume widths

predicted by the PGT dispersion curves with those measured by the aircraft is presented in table A-1 for the cases used in model evaluation (plume width is assumed to be equal to 4 σ_y). In the three cases for which the predicted plume width is greater than the measured plume width, the airplane probably missed the center of the plume; thus, the measured plume width is most likely smaller than the actual plume width. Among the remaining cases, 28 June and 13 July are the only days on which the plume width is overpredicted. It should be noted, however, that the use of SO_2 concentration measurements can lead to some uncertainty in the measured plume width because of the slow time response of the SO_2 monitor (Seigneur et al., 1981).

Because such a comparison of predicted and measured plume widths is strongly dependent on the assumption of a Gaussian plume model, it is interesting to evaluate the validity of the Gaussian approximation. Figure A-1 shows the measured NO_x concentration profile for the flight path traverse of 13 July, along with the Gaussian profile, which was determined from the maximum NO_x concentration and the total plume NO_x concentration integrated along the flight path. It appears that for this case the Gaussian profile provides a fairly good approximation of the actual profile. However, in some other cases, wind shear distorted the plume and the measured profiles were then non-Gaussian (e.g., the 15 December case studies).

Other useful indirect measures of plume dispersion are plume concentrations. Concentrations of NO_2 and the value of b_{sp} (particulate scattering coefficient) integrated along the sight path are shown in table A-2. The measured values were corrected for the angle between the flight path and the sight path. These values are of particular interest in conducting plume visibility model performance evaluation because they are the input to the optics module. Concentrations of NO_x at the plume centerline are presented in table A-3, along with the corresponding NO_2/NO_x ratios, which will be considered next in the discussion of evaluation of the chemistry module. Statistics concerning model performance for these variables are listed in table A-4.

TABLE A-1. COMPARISON OF PREDICTED AND MEASURED PLUME WIDTHS*

Day	Flight Number	Measured Plume Width (km) SO_2 > 20 ppb	Predicted Plume Width (km)
28 June	5	0.52	2.42
	7	2.80	4.30
13 July	1	3.70	5.73
4 December	2	12.18	1.73
	3	9.34	2.86
	4	6.79	3.25
	5	8.53	3.86
	12	18.10	2.52
7 December (morning)	2†	1.86	3.53
	3	6.30	3.53
	4	2.90	2.23
	7	5.11	3.46
	8	4.95	3.56
	9†	2.75	2.54
	10	7.56	1.88
	11	7.74	1.12
7 December (afternoon)	1	8.66	1.58
	2	9.22	2.20
	3	8.50	2.28
	4†	0.50	2.90
	5†	1.19	3.64
	7	13.0	3.61
15 December	2	10.92	2.90
	3	11.10	2.60
	7	8.26	3.65
	9	15.70	4.54

* Predicted plume widths are assumed to be equal to 4 σ_y, where σ_y is the Pasquill-Gifford horizontal dispersion coefficient. Measured plume widths are defined from SO_2 concentrations above 20 ppb.

† The aircraft probably did not fly through the plume center.

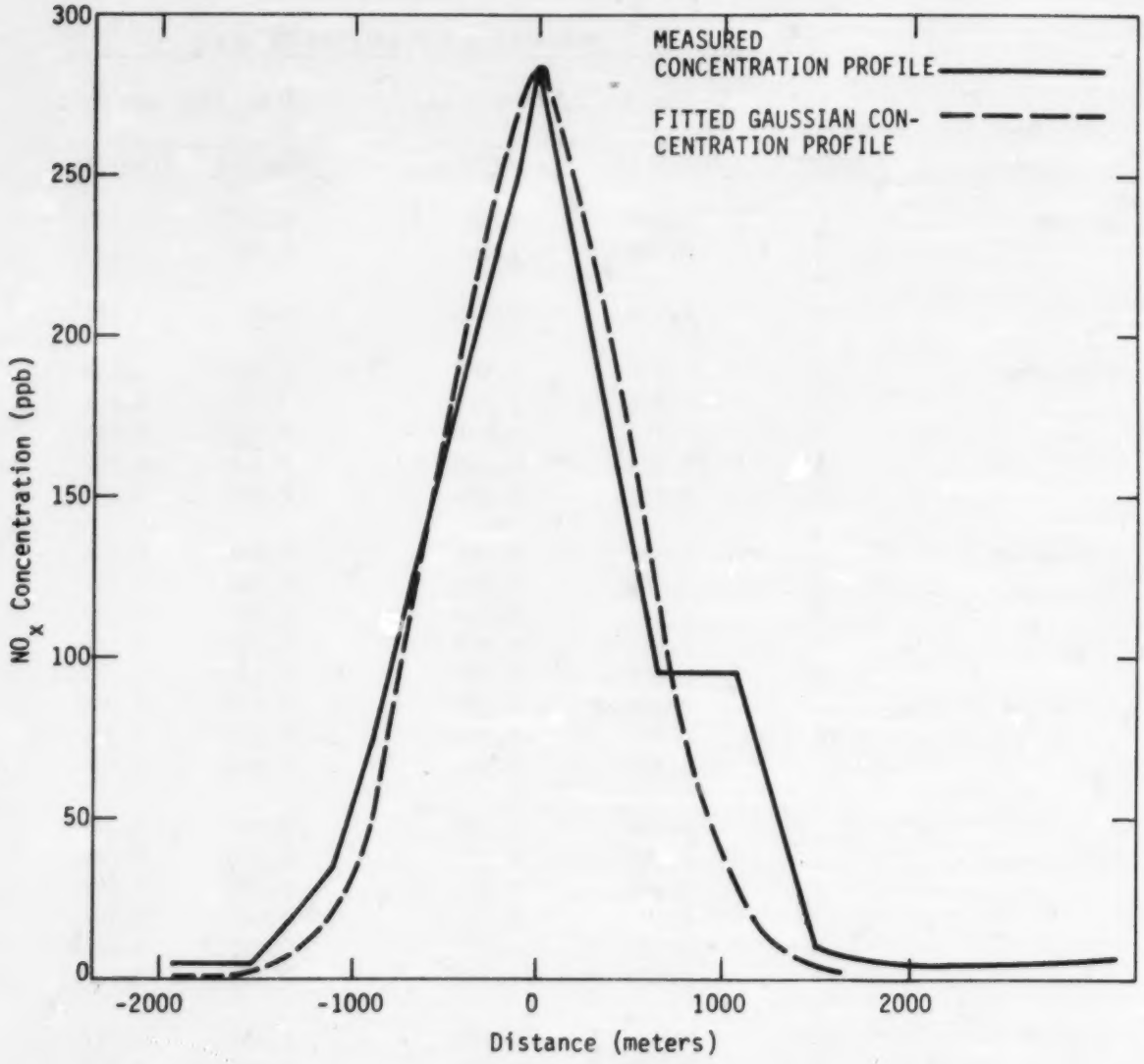


Figure A-1. Comparison of measured and Gaussian-fitted concentrations profiles for the 13 July 1979 case study.

TABLE A-2. COMPARISON OF MEASURED AND PREDICTED INTEGRATED NO_2 CONCENTRATIONS AND SCATTERING COEFFICIENT VALUES ALONG THE SIGHT PATH

Day (1979)	Flight Number	Measured and Predicted Values: $\int_0^L [NO_2] \cdot dy$ (ppm · km)		Measured and Predicted Values: $\int_0^L b_{sp}(550\ nm)\ dy$	
		Measured	Predicted	Measured	Predicted
28 June	5	0.085	0.566	0.121	1.028
	7	0.170	1.051	0.200	1.192
13 July *	1	0.170	0.245	0.01	0.153
4 December	2	--	0.573	0.349	0.589
	3	0.355	0.512	0.154	0.411
	4	0.318	0.436	0.131	0.349
	5	0.384	0.358	0.149	0.282
	12	0.880	0.279	0.438	0.304
7 December (morning)	2†	0.044	0.265	0.024	0.166
	3	0.158	0.268	0.094	0.161
	4	0.069	0.217	0.067	0.182
	7	0.190	0.268	0.157	0.166
	8	0.174	0.284	0.123	0.170
	9†	0.048	0.207	0.024	0.166
	10	0.281	0.203	0.206	0.206
	11	0.274	0.183	0.246	0.304
7 December (afternoon)	1	0.236	0.149	0.097	0.176
	2	0.250	0.171	0.106	0.149
	3	0.234	0.177	0.088	0.149
	4†	0.007	0.206	0.003	0.387
	5†	0.029	0.336	0.010	0.171
	7	0.482	0.352	0.161	0.192
15 December	2	--	0.683	1.409	0.737
	3	0.415	0.231	0.290	0.324
	7	0.520	0.470	0.323	0.361
	9	0.302	0.476	0.337	0.364

* Sight path from the Kaibito City telephotometer site.

† The aircraft probably did not fly through the plume center.

TABLE A-3. COMPARISON OF MEASURED AND PREDICTED NO_x MAXIMUM CONCENTRATIONS AND NO_2/NO_x RATIOS

Day (1979)	Flight Number	Measured and Predicted Values			
		NO_x (ppm)		$[NO_2]/[NO_x]$	
		Measured	Predicted	Measured	Predicted
28 June	5	0.122	1.410	0.402	0.191
	7	0.061	0.219	0.361	0.210
13 July	1	0.282	0.105	0.181	0.400
4 December	2*	--	2.413	--	0.227
	3	0.766	1.135	0.111	0.272
	4	0.427	0.819	0.124	0.258
	5	0.144	0.433	0.278	0.222
	12	0.483	0.821	0.128	0.173
7 December (morning)	2†	0.217	0.456	0.143	0.184
	3	0.251	0.458	0.175	0.188
	4§	0.698	0.900	0.138	0.147
	7	1.021	0.478	0.112	0.184
	8§	1.288	0.460	0.092	0.189
	9†	0.636	0.752	0.113	0.152
	10	1.215	1.189	0.091	0.125
	11	0.926	2.632	0.075	0.082
7 December (afternoon)	1	0.393	1.286	0.117	0.103
	2	0.238	0.780	0.189	0.131
	3	0.209	0.744	0.211	0.134
	4†	0.044	0.518	0.295	0.162
	5†	0.044	0.373	0.455	0.196
	7	0.223	0.450	0.206	0.196
15 December	2*	--	0.605	--	0.183
	3	1.496	0.712	0.123	0.173
	7	0.786	0.435	0.155	0.209
	9	0.457	0.317	0.184	0.237

* NO/NO_x measurements are unavailable.

† The aircraft probably did not fly through the plume center.

§ Uncertainty in the NO/NO_x measurements; NO_2 measured value is likely to be too low.

TABLE A-4. PERFORMANCE ANALYSIS OF PLUVUE DISPERSION AND CHEMISTRY MODULES FOR 15 CASE STUDIES UNDER CLEAR-SKY BACKGROUND CONDITIONS

Performance Measure	Plume Width*	NO_x Plume Centerline Concentration†	NO_2/NO_x at Plume Centerline†	$\int[NO_2]\,dy$†	$\int b_{sp} \cdot dy$*
Linear Regression					
Measured mean value	8.24	0.68	0.14	0.26	0.16
Predicted mean value	2.99	0.78	0.18	0.26	0.22
Correlation coefficient	0.009	0.225	0.401	0.360	0.912
Residual Statistics					
Bias	5.250	-0.104	-0.032	-0.005	-0.054
Bias confidence interval	±1.671	±0.364	±0.042	±0.071	±0.054
Variance	13.442	0.464	0.005	0.015	0.001
True variance confidence interval	7.950-28.643	0.270-1.026	0.003-0.011	0.008-0.0032	0.0007-0.0025
Root-mean-square error	6.33	0.665	0.076	0.115	0.066

* 15 case studies, selected from the clear-sky background cases, were used in the analysis. Cases in which the plane missed the plume centerline were discarded.

† 14 case studies, selected from the clear-sky background cases, were used in the analysis. Cases in which the plane missed the plume centerline and for which no NO/NO_x measurements were available were discarded.

The following conclusions can be drawn:

- Plume widths are generally underpredicted by the model. Cases for which the plume width is overpredicted correspond to those for which the aircraft probably missed the center of the plume; thus, the measured plume width is most likely smaller than the actual plume width. Among the remaining cases, 28 June and 13 July are the only days on which the plume width is overpredicted.

- The NO_x plume concentrations at plume center are generally overpredicted by the model, which is consistent with the underprediction of plume dispersion. In some cases, however, the NO_x plume cncentrations are underpredicted, suggesting that vertical plume dispersion was highly overpredicted or that the concentration distributions were non-Gaussian for these cases (on 13 July when plume width was overpredicted, and cases 7, 8, and 10 on the morning of 7 December, and all cases on 15 December).

- The correlation coefficient for the plume width is an extremely low value of 0.09; the correlation for the NO_x plume centerline is better, with a coefficient of 0.225. The treatment of horizontal plume dispersion is not critical in plume visibility modeling because the horizontally integrated plume values are used as input to the optics module. Horizontal plume dispersion thus affects model prediction mainly through the description of plume chemistry, which depends on the mixing of plume concentrations (e.g., NO) with background species (e.g., O_3).

- Tables A-1, A-2, and A-3 show that the agreement between measured and predicted plume integrated values is actually better than those for plume widths and NO_x plume centerline concentrations. The correlation coefficients are

0.360 and 0.912 for the NO_2 and b_{sp} integrated plume values. Overall, the NO_2 integrated plume values are slightly underpredicted by the model, whereas overall, the b_{sp} integrated plume values are overpredicted.

A.2 EVALUATION OF THE CHEMISTRY MODULE

The chemistry module of PLUVUE involves nine reactions among NO, NO_2, O_3, O_2, SO_2, OH, H_2O, and $O(^1D)$ (Latimer et al., 1980). This mechanism describes the main chemical processes occurring in power plant plumes in a clean background atmosphere. If notable concentrations of reactive hydrocarbons are present in the background, a more detailed mechanism should be used (e.g., Stewart and Liu, 1981). Hydrocarbon concentrations in the vicinity of the Navajo Generating Station were low enough to apply the plume visibility model mechanism for a clean atmosphere (Sheppard et al., 1980).

Since NO_2 absorbs light in the blue range, it is important to compare the predicted and measured rates of conversion of NO to NO_2. Oxidation of NO to NO_2 occurs both by molecular oxygen in the high-temperature flue gases and by ozone in the atmosphere.

It has been shown (Bergstrom et al., 1981) that the molecular oxidation of NO to NO_2 by O_2 accounts for an NO_2/NO_x ratio of about 5 percent. This agrees well with the values of 3 to 6 percent deduced from the airborne measurements (Richards et al., 1981).

Because oxidation of NO by O_3 in the plume is limited by the mixing of the plume with ambient air, the validity of the NO-NO_2-O_3 model depends to a great extent on the description of the plume dispersion processes. It can be evaluated by comparing the value of the NO_2/NO_x ratio predicted by the model with that measured in the plume. The predicted and measured NO_2/NO_x ratios are presented in table A-3 for the 27 case studies considered in the plume visibility model evaluation. It is appropriate to

discard cases in which the aircraft most likely did not fly through the plume center (cases 2 and 9--7 December morning; cases 4 and 5--7 December afternoon) and cases showing uncertainty in the NO_2 measurements (cases 4 and 8--7 December morning). For the remaining 18 cases for which NO_2 and NO_x measurements are reliable, there is good agreement between observed and predicted values because the average absolute relative error of the model is 45 percent. There is some bias toward overestimation of the NO_2 formation rate since the bias is -0.032 and the predicted NO_2/NO_x ratio is larger than the measured value in 11 out of 18 cases.

Plume chemistry measurements were also carried out by the MRI aircraft during one-hour orbit flights in the plume ranging from downwind distances of 25 to 100 km. It is interesting to evaluate the chemistry module with these time-averaged data because they were obtained at larger downwind distances than were those considered for the plume visibility model evaluation. To compare model predictions and measurements, it is necessary to make some assumptions for calculations of the plume average concentrations. The aircraft measures plume concentrations for one hour while performing an orbit in the plume. Since plume concentrations vary according to the location of the air sample in the plume, a procedure for calculating the plume averages from the model predictions must be defined. The plume generally becomes well mixed vertically at large downwind distances, and the uncertainties in the plume-concentration-averaging technique should not have a significant effect on the validity of the comparisons. In this study, the plume model averages were defined as the crosswind concentration average at the height of the plume centerline, and the plume dispersion was adjusted so that the average NO_x concentrations fit the measurements.

Table A-5 presents a comparison of the predicted and measured plume average NO_2/NO_x ratios for 10 cases selected from the December 1979 VISTTA field program. The agreement between model predictions and airborne measurements is good, especially when one takes into consideration the uncertainties associated with the averaging techniques. The average absolute relative error between the predictions of the plume visibility

model and the measurements of NO_2/NO_x is 25 percent. The average signed relative error is 19 percent. These results show that the NO_2/NO_x ratio is slightly overpredicted by the model.

TABLE A-5. COMPARISON OF MEASURED AND PREDICTED NO_2/NO_x RATIOS--ONE-HOUR TIME-AVERAGED PLUME CONCENTRATIONS

Day (1979)	Downwind Distance (km)	NO_2/NO_x Concentrations (ppm)		
		Measured	Predicted Plume Visibility Model	Predicted Reactive Plume Model
5 December	33	0.35	0.30	0.33
	80	0.71	0.61	0.73
9 December	30	0.20	0.30	0.29
	84	0.62	0.71	--
12 December	45	0.23	0.36	--
	77	0.48	0.65	--
	93	0.60	0.68	--
13 December	25	0.23	0.29	--
	65	0.48	0.60	--
	82	0.68	0.67	--

Three case studies were also modeled by the reactive plume model, which involves 70 reactions among 35 chemical species and provides a fairly detailed treatment of the chemical interactions between the plume and the background (Seigneur, 1982; Stewart and Liu, 1981). The results shown in table A-5 indicate that the plume visibility model with its nine-step reaction scheme compares favorably with the more detailed reactive plume model. This good agreement between model predictions and measurements suggests that the nine-step chemical mechanism of the PLUVUE is suitable for describing plume chemistry in clean environments in which reactive hydrocarbon concentrations are low.

Treatment of plume dispersion is likely to be the primary source of uncertainty in predicting chemical rates, because these rates depend on

the mixing of the plume material with the ambient air. Modeling the interactions of plume dynamics and chemistry, a subject mentioned by Bergstrom et al. (1981), requires further investigation.

A.3 EVALUATION OF THE OPTICS MODULE

The optics module calculates the plume's radiative properties and their optical effects. This module was evaluated using the plume concentrations of NO_2 and particulates measured by the airplane along a flight path aligned with the telephotometer line of sight. The best data were obtained on 7 December, the day on which 24 telephotometer sight paths were flown. The comparison of measured and predicted values for the 10 remaining flights are shown in table A-6 for the four wavelengths.

The results of the optics module performance evaluation are shown in table A-7. There is good correlation between measured and predicted plume/sky intensity ratios at 405, 450, and 550 nm, with correlation coefficients of 0.697, 0.843, and 0.768, respectively. There is a negative correlation (-0.210) at 630 nm; however, because plume contrasts are small at that wavelength, predicted and measured values are sensitive to uncertainties. Good correlation (0.888) is obtained for the blue/red ratio. Values of the bias show that PLUVUE, on the average, overestimates the plume optical effects at all wavelengths.

TABLE A-6. COMPARISON OF MEASURED AND PREDICTED PLUME/SKY INTENSITY RATIOS--PLUVUE OPTICS MODULE EVALUATION

Day (1979)	Flight Number	Time (MST)	Downwind Distance (km)	Observer Plume Distance (km)	Background Conditions	I^P/I^S (nm)							
						Measured (405)	Predicted (400)	Measured (450)	Predicted (450)	Measured (550)	Predicted (550)	Measured (630)	Predicted (650)
7 December	3	0929	21.25	16.0		0.925	0.846	0.926	0.838	0.942	0.918	0.973	0.948
(morning)	4	0949	11.75	11.7		0.894	0.908	0.915	0.908	0.934	0.953	0.954	0.970
	7	1030	20.80	17.7	Blue sky	0.902	0.831	0.899	0.815	0.942	0.892	0.985	0.926
	8	1044	21.50	19.0		0.890	0.851	0.876	0.837	0.935	0.910	1.000	0.940
	10	1135	9.30	20.4		0.900	0.801	0.881	0.775	0.927	0.867	0.979	0.907
	11	1154	4.30	16.3		0.819	0.770	0.779	0.750	0.860	0.854	0.959	0.903
7 December	1	1409	7.75	16.5		0.830	0.798	0.844	0.788	0.925	0.901	0.969	0.944
(afternoon)	2	1427	12.00	16.6	Blue sky	0.830	0.788	0.810	0.778	0.925	0.894	0.975	0.939
	3	1438	12.50	11.9		0.851	0.760	0.818	0.765	0.919	0.901	0.981	0.949
	7	1540	22.00	26.3		0.773	0.770	0.777	0.720	0.863	0.839	0.976	0.902

TABLE A-7. OPTICS MODULE PERFORMANCE ANALYSIS OF 10 CASE STUDIES

Performance Measure	Plume/Sky Intensity Ratios; Plume Contrasts* (Wavelength--nm) 405	450	550	630	Blue/Red Ratio
Linear Regression					
Measured mean value	-0.14	-0.15	-0.08	-0.03	0.88
Predicted mean value	-0.19	-0.20	-0.11	-0.07	0.85
Correlation coefficient	0.697	0.843	0.768	-0.210	0.888
Residual Statistics					
Bias	0.0491	0.0551	-0.0243	0.0415	+0.0209
Bias confidence interval	±0.0386	±0.0444	±0.0259	±0.0156	±0.0418
Variance	0.0014	0.0009	0.0005	0.0009	0.0008
True variance confidence interval	0.0007-0.0037	0.0005-0.0025	0.0003-0.0013	0.0005-0.0023	0.0004-0.0021
Root-mean-square error	0.060	0.062	0.032	0.050	0.033
Normalized Residual Statistics					
E_1	0.060	0.064	0.030	0.048	0.031
$S_{1\dagger}$	0.056	0.064	0.027	0.043	0.026
$E_{2\dagger}$	0.47	0.45	0.39	1.64	--
S_2	-0.45	-0.45	-0.33	-1.51	--

* Linear regression and nonnormalized residual statistics are listed for the plume contrasts; E_1 and S_1 correspond to plume/sky intensity ratios, and E_2 and S_2 correspond to plume contrasts.

† Cases with measured absolute plume contrast of less than 0.02 were discarded from the calculation; the total number of cases were 10, 10, 10, and 8 at 405, 450, 550, and 630 nm.

APPENDIX B

EVALUATION OF THE MODULES OF THE ERT VISIBILITY MODEL

B.1 EVALUATION OF THE DISPERSION MODULE

The dispersion module of the ERT Visibility Model employs a Gaussian formulation of the dispersion of nonreactive pollutants. In this section, we evaluate the dispersion module using a comparison of selected measured and predicted plume values. Values that can be used to evaluate the adequacy of model treatment of plume dispersion include plume width and plume NO_x concentrations at centerline: plume concentrations at the centerline of the plume are an indirect measure of total plume dispersion.

In addition to plume widths and plume centerline concentrations, plume concentrations integrated across the plume are also of interest because they provide an indirect measure of plume vertical dispersion.

Table B-1 compares measured and predicted values for plume widths, NO_x concentrations at plume centerline, the NO_2/NO_x ratio at plume centerline (which is used in the plume chemistry module evaluation), integrated NO_2 concentrations, and the particle-scattering coefficient along the line of sight in the plume. The results of a linear regression analysis of these values along with residual statistics, are presented in table B-2. The results presented in these tables suggest the following conclusions:

- Plume widths are generally underpredicted by the model. Cases for which the plume width is overpredicted correspond to cases in which the aircraft probably missed the

TABLE B-1. COMPARISON OF SELECTED PREDICTED AND MEASURED PLUME VALUES

Day (1979)	Flight Number	Plume Widths (km)		NO_x Plume Centerline Concentration (ppm)		NO_2/NO_x at Plume Centerline		$\int[NO_2]\,dy$** (ppm-km)		$\int b_{sp}$ (550 nm) * dy**	
		Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted
28 June	5	0.52	1.84	0.122	2.238	0.402	0.067	0.085	0.292	0.121	1.475
	7	2.80	4.05	0.061	0.249	0.361	0.180	0.170	0.879	0.200	1.515
13 July*	1	3.70	5.52	0.282	0.110	0.181	0.387	0.170	0.216	0.010	0.163
4 December	2§	12.18	1.52	--	3.107	--	0.062	--	0.225	0.349	0.823
	3	9.34	2.54	0.766	1.414	0.111	0.077	0.355	0.206	0.154	0.546
	4	6.79	2.94	0.427	0.982	0.124	0.088	0.318	0.217	0.131	0.480
	5	8.53	3.64	0.144	0.494	0.278	0.123	0.384	0.241	0.149	0.368
	12	18.10	2.33	0.483	0.930	0.128	0.090	0.880	0.179	0.438	0.392
7 December (morning)	2†	1.86	3.17	0.217	0.567	0.143	0.109	0.044	0.194	0.024	0.297
	3	6.30	3.17	0.251	0.567	0.175	0.115	0.158	0.203	0.094	0.254
	4	2.90	1.88	0.698	1.258	0.138	0.082	0.069	0.161	0.067	0.302
	7	5.11	3.12	1.021	0.583	0.112	0.113	0.190	0.201	0.157	0.244
	8	4.95	3.21	1.288	0.559	0.092	0.117	0.174	0.211	0.123	0.250
	9†	2.75	2.20	0.636	0.992	1.113	0.088	0.048	0.156	0.024	0.255
	10	7.56	1.53	1.215	1.732	1.091	0.072	0.281	0.160	0.206	0.333
	11	7.74	0.76	0.926	5.105	0.075	0.057	0.274	0.183	0.246	0.548
7 December (afternoon)	1	8.66	1.30	0.393	1.864	0.117	0.071	0.236	0.136	0.097	0.253
	2	9.22	1.91	0.238	1.019	0.189	0.087	0.250	0.139	0.106	0.202
	3	8.50	1.99	0.209	0.964	0.211	0.089	0.234	0.139	0.088	0.199
	4†	0.50	2.61	0.044	0.636	0.295	0.111	0.007	0.158	0.003	0.183
	5†	1.19	3.34	0.044	0.440	0.455	0.140	0.029	0.254	0.010	0.228
	7	13.0	3.27	0.223	0.543	0.206	0.118	0.482	0.237	0.161	0.279

TABLE B-1 (Concluded)

Day (1979)	Flight Number	Plume Widths (km)		NO_x Plume Centerline Concentration (ppm)		NO_2/NO_x at Plume Centerline		$\int[NO_2]\,dy$** (ppm-km)		$\int b_{sp}$ (550 nm) • dy**	
		Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted
15 December	2§	10.92	2.70	--	0.718	--	0.107	--	0.423	1.409	0.748
	3	11.10	1.284	1.496	1.287	0.123	0.082	0.415	0.174	0.290	0.436
	7	8.26	4.36	0.786	0.358	0.155	0.159	0.520	0.361	0.323	0.443
	9	15.70	4.46	0.457	0.347	0.184	0.159	0.302	0.360	0.337	0.451

* Sight path from the Kaibito City telephotometer site.

† The aircraft probably did not fly through the plume center.

§ NO/NO_x measurements are unavailable.

** Value integrated in the plume along the sight path. Corrections were made when the flight path did not correspond to the sight path.

TABLE B-2. ERT DISPERSION AND CHEMISTRY MODULES PERFORMANCE ANALYSIS OF 15 CASE STUDIES UNDER CLEAR-SKY BACKGROUND CONDITIONS

Performance Measure	Plume Width[§]	NO_x Plume Centerline Concentration[†]	NO_2/NO_x at Plume Centerline[†]	$\int[NO_2]\,dy$[†]	$\int b_{sp} * dy$[§]
Linear Regression					
Measured mean value	8.24	0.68	0.14	0.26	0.16
Predicted mean value	2.73	1.16	0.12	0.21	0.31
Correlation coefficient	0.020	0.250	0.361	0.325	0.843
Residual Statistics					
Bias	5.507	-0.4866	0.0241	0.0531	-0.1501
Bias confidence interval	±1.69	±0.6280	±0.0449	±0.0620	±0.0659
Variance	13.635	1.4821	0.0063	0.0120	0.0041
True variance confidence interval	8.06-29.06	0.8617-3.2712	0.0036-0.0138	0.0070-0.0265	0.0024-0.0091
Root-mean-square error	6.56	1.27	0.080	0.118	0.162

§ 15 Case studies were used in the analysis. Cases were selected from the clear sky background cases. Cases when the plane missed the plume centerline were discarded (see table 6).

† 14 case studies were used n the analysis. Cases were selected from the clear sky background cases. Cases when the plane missed the plume centerline and for which no NO/NO_x measurements were available, were discarded (see table 6).

center of the plume; thus, the measured plume width is most likely smaller than the actual plume width. Among the remaining cases, 28 June and 13 July are the only days on which the plume width is overpredicted.

- The NO_x plume concentrations at plume center are generally overpredicted by the model, a result that is consistent with the underprediction of plume dispersion. In some cases, however, the NO_x plume concentrations are underpredicted, suggesting that vertical plume dispersion was highly overpredicted or that the concentration distributions were non-Gaussian for these cases (cases 7 and 8 on the morning of 7 December; all cases on 15 December).

- The correlation coefficient for the plume width is an extremely low value of 0.02; the correlation for the NO_x plume centerline is better, with a coefficient of 0.250. The treatment of horizontal plume dispersion is not critical in plume visibility modeling because the horizontally integrated plume values are used as input to the optics module. Horizontal plume dispersion thus affects model prediction mainly through the description of plume chemistry, which depends on the mixing of plume concentrations (e.g., NO) with background species (e.g., O_3).

- Tables B-1 and B-2 show that the agreement between measured and predicted plume integrated values is actually better than those for plume widths and NO_x plume centerline concentrations. The correlation coefficients are 0.325 and 0.843 for the NO_2 and b_{sp} integrated plume values. Overall, the NO_2 integrated plume values are slightly underpredicted by the model, whereas overall, the b_{sp} integrated plume values are overpredicted.

B.2 EVALUATION OF THE CHEMISTRY MODULE

The chemistry module of the ERT Visibility Model is based on the chemistry of NO, NO_2, and O_3. Because NO_2 absorbs light in the blue range, it is important that this evaluation compare the predicted and measured rates of conversion of NO to NO_2. Oxidation of NO to NO_2 occurs both by O_2 in the high-temperature flue gases and by O_3 in the atmosphere.

Since oxidation of NO by O_3 in the plume is limited by the mixing of the plume with ambient air, the validity of the $NO\text{-}NO_2\text{-}O_3$ chemistry module depends to a great extent on the description of the plume dispersion processes; it can be evaluted by comparing the value of the NO_2/NO_x ratio predicted by the model with that measured in the plume. The predicted and measured NO_2/NO_x ratios are presented in table B-1 for the 27 case studies considered in the visibility model evaluation. The two case studies of 13 July are listed as only one in table B-1, because they correspond to the same flight path. For this evaluation, it is appropriate to discard cases in which the aircraft most likely did not fly through the plume center (cases 2 and 9--7 December morning; cases 4 and 5--7 December afternoon) and cases containing uncertainties in the NO_2 measurements (cases 4 and 8--7 December morning).

There is a slight trend toward underestimation of the NO_2/NO_x ratio since the bias is 0.024 compared with the mean measured value of 0.14. As indicated in table B-1, most cases show good agreement between the measured and predicted values of the NO_2/NO_x ratio. It is difficult, however, to evaluate individual uncertainties associated with the chemistry module because of its close interaction with the dispersion module.

B.3 EVALUATION OF THE OPTICS MODULE

The optics module of the ERT Visibility Model was evaluated using 10 case studies from 7 December. The plume and background concentrations measured by the aircraft along the sight path were used as input. The

values used were NO_2 concentrations and scattering coefficient values at 550 nm. Aerosols were assumed to be noncarbonaceous.

Average values were assumed for the background both before and after the aircraft entered the plume. Measurements of NO_2 concentrations and scattering coefficient values were averaged over 10-second intervals, which correspond to distance increments of 700 m along the sight path because the aircraft speed was about 70 m sec^{-1}. The results of the 10 simulations are presented in table B-3.

The results of the performance analysis are presented in table B-4 for the plume/sky intensity ratios, plume contrast, and blue/red ratio. The results indicate good correlation between measured and predicted plume contrast in the blue light range, with correlation coefficients of 0.816 and 0.823 at 405 and 450 nm, respectively. The correlation is less satisfactory at 550 nm, with a correlation coefficient of 0.482, and it is negative at 630 nm, with a correlation coefficient of -0.401. A possible explanation for this poor agreement is that the plume visual effects at 550 and 630 nm are not as important as they are in the blue light range; thus, the measurements and model predictions are more sensitive to uncertainties at the greater wavelength. Reasonably good correlation is obtained for the blue/red ratio. For comparison, the correlation between the plume contrasts predicted by the PLUVUE optics module and the measured values were 0.70, 0.84, 0.77, and -0.21 at 405, 450, 550, and 630 nm.

The values of the bias and S_1 (normalized bias) indicate that the ERT Visibility Model underestimates the plume visual effects. The absolute average normalized errors, E_2, in plume contrasts are 46, 34, 21, and 51 percent at 405, 450, 550, and 630 nm. For comparison, the PLUVUE optics module overestimated the plume visual effects for most cases--the absolute average normalized errors, E_2, were 47, 45, 39, and 164 percent at the same wavelengths.

Taking into account uncertainties in the measurements and input data, performance of the ERT optics module appears to be satisfactory.

TABLE B-3. COMPARISON OF MEASURED AND PREDICTED PLUME/SKY INTENSITY RATIOS FOR THE ERT OPTICS MODULE EVALUATION

Day (1979)	Flight Number	Time (MST)	Downwind Distance (km)	Observer Plume Distance (km)	Background Conditions	I^P/I^S Measured (405 nm)	Predicted (400 nm)	Measured (450 nm)	Predicted (450 nm)	Measured (550 nm)	Predicted (550 nm)	Measured (630 nm)	Predicted (650 nm)
7 December (morning)	3	0929	21.25	16.0		0.925	0.933	0.926	0.915	0.942	0.942	0.973	1.001
	4	0949	11.75	11.7		0.894	0.933	0.915	0.917	0.934	0.956	0.946	1.041
	7	1030	20.80	17.7	Blue sky	0.902	0.936	0.899	0.919	0.942	0.947	0.985	1.005
	8	1044	21.50	19.0		0.890	0.935	0.876	0.918	0.935	0.946	1.000	1.004
	10	1135	9.30	20.4		0.900	0.939	0.881	0.922	0.927	0.945	0.979	1.012
	11	1154	4.30	16.3		0.819	0.914	0.779	0.892	0.860	0.926	0.959	1.033
7 December 1979 (afternoon)	1	1409	7.75	16.5		0.830	0.949	0.844	0.934	0.925	0.951	0.969	0.999
	2	1427	12.00	16.6	Blue sky	0.830	0.952	0.810	0.939	0.925	0.958	0.975	1.003
	3	1438	12.50	11.9		0.851	0.948	0.818	0.935	0.919	0.961	0.981	1.013
	7	1540	22.00	26.3		0.773	0.928	0.777	0.911	0.863	0.943	0.976	1.004

TABLE B-4. ERT OPTICS MODULE PERFORMANCE ANALYSIS OF 10 CASE STUDIES

Performance Measure	Plume/Sky Intensity Ratios; Plume Contrasts* Wavelength (nm)† 405	450	550	630	Blue-Red Ratio
Linear Regression					
Measured mean value	-0.14	-0.15	-0.08	-0.03	0.88
Predicted mean value	-0.07	-0.09	-0.08	-0.01	0.94
Correlation coefficient	0.816	0.823	0.482	-0.401	0.679
Residual Statistics					
Bias	-0.0683	-0.0582	-0.0015	-0.0110	-0.0684
Bias confidence interval	±0.0291	±0.0331	±0.0181	±0.0103	±0.0354
Variance	0.0014	0.0018	0.0008	0.0004	0.0022
True variance confidence interval	0.007-0.0037	0.0009-0.0048	0.0004-0.0020	0.0002-0.0012	0.0012-0.0060
Root-mean-square error	0.0059	0.0050	0.0007	0.0005	0.0067
Normalized Residual Statistics†					
E_1	0.080	0.071	0.021	0.016	0.085
S_1	-0.080	-0.071	-0.003	-0.012	-0.081
E_2§	0.462	0.342	0.210	0.511	--
S_2§	0.462	0.342	-0.061	0.511	--

* Linear regression and nonnormalized residual statistics are listed for the plume contrasts.

† Wavelengths listed correspond to wavelength of measurement; model predictions are at 400, 450, 550, and 650 nm. Normalized residual statistics E_1 and S_1 correspond to plume/sky intensity ratios, whereas E_2 and S_2 refer to plume contrasts.

§ Cases with measured absolute plume contrast of less than 0.02 were discarded from the calculation; the total number of cases were 10, 10, 10, and 8 at 405, 450, 550, and 630 nm.

APPENDIX C

SENSITIVITY/UNCERTAINTY ANALYSIS OF PLUVUE

The degree of agreement that can be obtained between model predictions and measurements is limited by the uncertainties associated with the measurements. It is, therefore, of interest to evaluate the uncertainties existing in the various measurements that constitute the data base used for model evaluation and to determine their effects on visibility model performance evaluation.

The procedure for conducting sensitivity/uncertainty analysis is as follows. First, the uncertainties in the input data used in a model simulation are defined. Then, the sensitivity of the model predictions to each model input parameter is determined. The combination of the degree of model sensitivity to an input parameter and the degree of uncertainty associated with this parameter provides a measure of the effect of uncertainties in an input parameter on the accuracy of model predictions. In practice, the sensitivity analysis of the model is directly combined with the uncertainty estimates, i.e., the sensitivity of the model to parameter uncertainties is calculated by introducing perturbations in the input parameter equal to the parameter uncertainties.

Flight 1 on the afternoon of 7 December was chosen for the sensitivity/uncertainty analysis. This case study presents a well-defined plume against a blue sky and a good telephotometer scan was obtained. A qualitative study of the plume visibility model sensitivity and of the uncertainties in the input data has been given elsewhere (Seigneur et al., 1980). On the basis of the results of the uncertainty/sensitivity study

conducted by Seigneur et al. (1980), seven input parameters were selected. These parameters are listed in table C-1 with their estimated uncertainties.

TABLE C-1. INPUT PARAMETERS FOR PLUVUE SENSITIVITY/UNCERTAINTY ANALYSIS

Model Input Parameter	Degree of Uncertainty
NO_x emission rate	13%
Primary aerosol emission rate	20%
Wind speed	40%
Wind direction	7°
Visual range	25%
Background ozone concentration	5 ppb
Aerosol size distribution	
Coarse mode mean radius	0.25 μm (plume) 0.5 μm (background)

The uncertainties in the NO_x and primary aerosol emission rates were chosen to be the standard deviations for the corresponding emission rates for the winter VISTTA field program. The wind speed was calculated from pibal data. Uncertainties were due to the temporal and spatial resolution of these data. From the variation in wind speed between different levels and measurement times, an uncertainty value of 40 percent was determined. The plume centerline location was defined from the SO_2 concentration profile measured by the aircraft. From the time response of the SO_2 monitor and aircraft speed, an uncertainty value on the order of 1 km was estimated. This corresponds to a 7° uncertainty value in the effective wind direction for the downwind distance considered.

The visual range is calculated from background nephelometer measurements. Uncertainties in the visual range value are due to measurement uncertainties as well as to the nonhomogeneous nature of the atmosphere (Babson et al., 1982). An uncertainty value of 25 percent was chosen for the visual range. The background ozone concentration affects the rate of formation of NO_2 in the plume. The uncertainty has been estimated to be about 5 ppb (Richards et al., 1981). The aerosol size distribution has some effect on the optical properties of the plume because light scattering depends on particle size. The uncertainty in the aerosol size distribution was limited to the coarse mode because there was no appreciable difference between the plumes and background accumulation mode aerosol size distributions. The uncertainties in the mean radii of the coarse mode were chosen to be 0.25 μm for the plume aerosol* and 0.5 μm for the background aerosol (Whitby and Sverdrup, 1978).

Sensitivity studies were carried out by independently perturbing each parameter by the uncertainty value listed in table C-1. For simplicity in analyzing the results, the parameters were perturbed to decrease plume visual effect. Thus, the wind speed, plume aerosol mean radius, and wind direction were increased, whereas the NO_x and primary aerosol emission rates, background ozone concentration, background aerosol mean radius, and visual range were decreased. A sensitivity study was also carried out by varying all seven parameters. The results of these eight sensitivity studies are shown in table C-2 for the ratios of plume/sky intensities at the four wavelengths.

It is apparent from the results shown in the table that uncertainties in the wind speed and visual range have the greatest effect on model predictions. Uncertainties in the wind speed are higher in the blue range (at 405 and 450 nm), where light absorption by NO_2 occurs, in part, because NO_2 concentrations are more affected than primary aerosol concentrations by a change in wind speed. A change of 40 percent in the wind

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* G. E. Palomino, private communication, 1981.

TABLE C-2. SENSITIVITY/UNCERTAINTY STUDIES OF PLUVUE--FLIGHT 1, AFTERNOON, 7 DECEMBER 1979

Input Parameter Perturbed	Original Value	Perturbed Value	Percentage Deviation in Plume/Sky Intensity Ratios (nm)			
			405	450	550	630
NO_x emission rate	97.3 tons/day	84.3 tons/day	1.40%	1.46%	0.44%	0.10%
Primary aerosol emission rate	8.43 tons/day	6.79 tons/day	0.31	0.61	1.11	1.17
Wind speed	2.4 m/sec^{-1}	3.4 m/sec^{-1}	3.49	4.04	2.54	1.88
Wind direction	103°	110°	0.66	0.54	0.18	0.11
Visual range	274.2 km	205.7 km	2.57	2.72	1.79	1.23
Background ozone concentration	0.034 ppm	0.029 ppm	0.72	0.76	0.23	0.05
Aerosol size distribution	3.0 μm (background)	2.5 μm (background)	0.06	0.61	0.79	0.75
Mean radii	1.75 μm (plume)	2.0 μm (plume)				
All parameters	As above	As above	7.49	8.63	5.49	4.08

speed leads to an equivalent change in primary aerosol concentrations, but to a 50 percent change in NO_2 concentrations because of the nonlinear relationship of NO_2 concentrations to NO_x emissions.

Uncertainties in the visual range also lead to larger deviations in plume/sky intensity ratios at shorter wavelengths. This result occurs because the plume visual effects at Navajo Generating Station are more important in the blue range and the model is, therefore, generally more sensitive in this range to perturbations that affect the whole visible range.

Changes in the NO_x emission rates have greatest effect in the blue range, which corresponds to the range of light absorption by NO_2. Negligible effect appears at 630 nm. Although emission rates of NO_x are known with reasonable accurcy, about 13 percent, the effect on model predictions is not negligible.

Uncertainties in primary aerosol emission rates are greater. However, aerosols do not contribute as much as NO_2 to the overall visual effects of the plume at the downwind distance considered. The effect of these uncertainties is at most 1.17 percent in the red and decreases with decreasing wavelength as the effect of NO_2 absorption becomes predominant.

Uncertainties in the mean radii of the coarse mode aerosols have a comparable effect on the model predictions. The value of the background ozone concentrations affect the formation of NO_2 in the plume. An uncertainty value of 5 ppb in the ozone concentrations corresponds to about 15 percent uncertainty. Thus, the model is about twice less sensitive to O_3 concentration than to NO_x emission rates.

The uncertainty in wind direction correspond to an uncertainty in the plume-observer distance of 6 percent. This does not induce any major perturbation in the model predictions.

When all these parameters were perturbed, large deviations occurred in the values of the predicted plume/sky intensity ratios. It should be noted, however, that this represents an upper limit of the total uncertainty in model predictions due to uncertainties in input data, because input data uncertainties may well compensate each other to some extent, thus leading to a lower deviation in model predictions. The perturbations in the plume/sky intensity ratios correspond with perturbations in plume contrast of 50, 50.5, 54.4, and 55.5 percent at 405, 450, 550, and 630 nm, respectively.

Comparison of telephotometer scans conducted at 5-minute time intervals showed that uncertainty in the telephotometer measurements of plume visual effects ranges from 0 to 5 percent. Since the relative deviations between the predicted and measured concentrations [(Predicted - Measured)/Predicted] are 4.5, 1.2, -2, and -4 percent at 405, 450, 550, and 630 nm, respectively, the agreement between model predictions and measurements is within the uncertainties in the input data and measurements for a run for which the plume is well defined.

APPENDIX D

MODIFICATIONS TO THE ERT VISIBILITY MODEL COMPUTER CODE

To evaluate the modules of the ERT Visibility Model, it was necessary to modify the computer code to obtain those output functions not provided by the original model output. Additional output functions needed for evaluation of the chemistry and dispersion modules included

- Centerline concentrations of NO_x, NO_2, and particulates.
- Values integrated across the plume (integral concentrations) for NO_2 concentrations.
- Values integrated across the plume (integral values) for the scattering coefficient of particulates (b_{sp}).

D.1 CENTERLINE CONCENTRATIONS

Integrated into the ERT Visibility Model was a method of determining pollutant concentrations at various distances, y, from the plume centerline (e.g., for equally spaced points along a given line of sight). By entering a particular downwind distance, DWDT, and setting y = 0, centerline concentrations for noncarbonaceous particulates, carbonaceous particulates, and NO_2 could be obtained. In the cases considered, centerline concentrations of NO_x were also of interest. NO_x concentrations were already determined by the model as an initial step to calculating NO_2; therefore, only a unit conversion factor and a common statement

remained to be added. To obtain the centerline concentrations of particulates, NO_2, NO_x, and O_3, the following steps were added to SUBROUTINE PLUME:

(1) The downwind distance, DWDT, was read in.

(2) SUBROUTINE SIGMA was called using DWDT to obtain SY and SZ, the horizontal and vertical dispersion parameters.

(3) SUBROUTINE VERT was called using SZ to obtain the vertical distribution function, VERT. Because the plume height at DWDT was unknown, the final plume height calculated was used.

(4) SUBROUTINE YDIF was then called, with the distance from the plume centerline set equal to zero. From this, the horizontal distribution function, YDIF, was obtained.

(5) CHIQ was then set equal to ZDIF*YDIF/UHP, as in the model, with UHP equal to the wind speed at stack height.

(6) CHIQ, DWDT, and the plume height above sea level were then used in a call to SUBROUTINE QF to obtain centerline concentrations for the particulates NO_2 and NO_x.

D.2 INTEGRAL PLUME VALUES

To obtain the integral values of b_{sp} and NO_2 concentrations across the plume along the line of sight, indices corresponding to the plume edges had to be determined. This was done in SUBROUTINE PLUME while the concentration field was being recorded along the line of sight from the observer to the visual range. The method used was to compare YABS, the absolute value of the distance from the plume centerline, with 2*SY at the corresponding downwind distance. When YABS was first found to be less

than, or equal to, 2*SY, the iteration number was set equal to NNBEG. As the concentration recording continued along the line of sight, a check for YABS > 2*SY was imposed. When YABS again became greater than, or equal to, 2*SY, the iteration number was set equal to NNEND. NNBEG and NNEND were then used as signals for the plume boundaries in SUBROUTINE RADTRA.

SUBROUTINE SIMPS was called at 550 nm using NNBEG and NNEND as integration/summing boundaries for noncarbonaceous particulates, carbonaceous particulates, and NO_2. The summed concentrations obtained were then multiplied by corresponding scattering and/or absorption coefficients. ($\int NO_2\, dy$ values were later divided by the absorption coefficients to obtain $\int NO_2\, dy$ in units of km^{-1}.)

Centerline NO_2 and NO_x concentrations and $\int NO_2\, dy$ values were converted from units of g/m^3 to ppm using 2.46×10^{10} ppm/(mole cm^{-3}), along with the respective molecular weights. The resultant values were then divided by 0.86 atmospheres to compensate for pressure.

REFERENCES

Babson, B. L., R. W. Bergstrom, M. A. Samuelson, C. Seigneur, A. Waggoner, and W. C. Malm (1982), "Statistical Analysis of Nephelometer Regional Field Data," Atmos. Environ., in press.

Bergstrom, R. W., B. L. Babson, and T. Ackerman (1981), "Calculation of Multiply Scattered Radiation in Clean Atmospheres," Atmos. Environ., Vol. 15, pp. 1821-1826.

Bergstrom, R. W., C. Seigneur, B. L. Babson, H. Y. Holman, and M. A. Wojcik (1981), "Comparison of the Observed and Predicted Visual Effects Caused by Power Plant Plumes," Atmos. Environ., Vol. 15, pp. 2135-2150.

Environmental Research and Technology, Inc. (1980), "ERT Visibility Model: Version 3--Technical Description and User's Guide," Document M-2020-001, Environmental Research and Technology, Inc., Concord Massachusetts.

Fox, D. G. (1981), "Judging Air Quality Model Performance," Bull. Am. Meteor. Soc., Vol. 62, pp. 599-609.

Friedlander, S. K. (1977), Smoke, Dust and Haze, Fundamentals of Aerosol Behavior, p. 143 (John Wiley & Sons, New York, New York).

Hudischewskyj, A. B., B. L. Babson, R. W. Bergstrom, and C. Seigneur (1981), "Coal-Fired Power Plant Contribution to Visibility Impairment in Western Pristine Areas--Index to the Photographs Taken from Telephotometer Sites during the June-July and December 1979 VISTTA Field Programs," 6-ES81-025, Systems Applications, Inc., San Rafael, California.

Johnson, C. D., D. A. Latimer, H. Hogo, and R. W. Bergstrom (1980), "User's Manual for the Plume Visibility Model (PLUVUE)," EPA-450/4-80-032, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina.

Latimer, D. A., R. W. Bergstrom, C. D. Johnson, and J. P. Killus (1980), "Modeling Visibility," Second Joint Conference on Applications of Air Pollution Meteorology, 27-29 March 1980, New Orleans, Louisiana.

Latimer, D. A., R. W. Bergstrom, S. R. Hayes, M. K. Liu, J. H. Seinfeld, G. Z. Whitten, M. A. Wojcik, and M. J. Hillyer (1978), "The Development of Mathematical Models for the Prediction of Anthropogenic Visibility Impairment," EPA-450/3-78-110a, b, and c, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina.

Richards, L. W., J. A. Anderson, D. L. Blumenthal, A. A. Brandt, J. A. McDonald, and N. Waters (1981), "The Chemistry, Aerosol Physics, and Optical Properties of a Western Coal-Fired Power Plant Plume," Atmos. Environ., Vol. 15, pp. 2111-2134.

Seigneur, C. (1982), "A Model of Sulfate Aerosol Dynamics in Atmospheric Plumes," Atmos. Environ., in press.

Seigneur, C., A. B. Hudischewskyj, B. L. Babson, R. W. Bergstrom, and S. Eigsti (1981), "Coal-Fired Power Plant Contribution to Visibility Impairment in Western Pristine Areas-VISTTA 1979 Interim Report-Part 2-Case Studies for Plume Visibility Model Validation," MRI 81 IR 1829, Meteorology Research, Inc., Santa Rosa, California.

Seigneur, C., R. W. Bergstrom, D. L. Blumenthal, L. W. Richards, E. S. Macias, W. E. Wilson, and P. S. Bhardwaja (1980), "The Data Base for Visibility Model Evaluation from the June-July and December 1979 EPA-VISTTA Field Programs," Symposium on Plumes and Visibility--Measurements and Model Components, 10-14 November 1980, Grand Canyon, Arizona.

Sheppard, J. C., M. Campbell, P. H. McMurry, and G. L. Kolk (1980), "Trace Gas and Particle Data from a Remote Site in Northern Arizona," unpublished results, Department of Civil Engineerinig, University of Washington, Seattle, Washington.

Stewart, D. A., and M. K. Liu (1981), "Development and Application of a Reactive Plume Model. Atmos. Environ., Vol. 15, pp. 2377-2393.

Whitby, K. T., and G. M. Sverdrup (1978), "California Aerosols: Their Physical and Chemical Characteristics," ACHEX Hutchinson Memorial Volume, Particle Technology Laboratory Publication Number 347, University of Minnesota, Minneapolis, Minnesota.